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Sampling strategies for soil water content to estimate evapotranspiration

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Abstract. When the soil water balance method is applied at a field scale, estimation of the spatial variability and confidence interval of actual evapotranspiration is rare, although this method is sensitive to the spatial variability of the soil, and thus to the sampling strategy. This work evaluated the effect of soil sampling strategies for soil water content and water flux at the bottom of the soil profile on the estimation of the daily and cumulative evapotranspirations. To do that, according to the statistical properties of daily measurements in a field experiment with a soybean crop, the water content and flux through the base to the soil profile in space (field scale) and time (daily scale) were simulated. Four different sampling strategies were then compared, and their effects on daily and seasonal cumulative evapotranspirations quantified. Strategy 1 used ten theoretical sites randomly located in the field. The daily water content estimates were assumed to be available each day from these same ten locations, which were located from 0.15 m to 1.55 m in depth, with space steps of 0.10 m. Strategy 2 assumed that daily water content estimates combined two sources: in the 0.00–0.20 m soil layer, ten theoretical sites were selected but changed every day, with thin soil layers for soil moisture sampling, from 1 to 5 cm in thickness. In the 0.20–1.60 m soil layer, the daily water content estimates were assumed to come from the same ten locations (the first soil moisture estimate was located at 0.25 m, and the others were located every 0.10 m until 1.55 m). Strategy 3 used ten theoretical sites located in the field, as in strategy 1, however the water content estimates in the 0.00–0.20-m soil layer were assumed to come from accurate water content measurements (soil layers from 1 to 5 cm in thickness), while for the 0.20–1.60 m soil layer, the strategy was similar to strategies 1 and 2. Strategy 4 used 10 new theoretical locations of measurement every day. Precise water content estimates for thin layers were assumed to be available in the 0.00–0.20 m soil layer as in strategy 2. The layers for water content estimates in the 0.20–1.60 m were similar to those of strategies 1, 2, and 3. Results showed that the spatial variability of the daily actual evapotranspiration may not be negligible, and differences from approximately ± 1.0 mm d^{-1} to ± 3.0 mm d^{-1} were calculated between the four sampling strategies. Strategy 1 gave the worst results, because variations in the water content of the top soil layers were neglected, and thus the daily evapotranspiration was underestimated. Strategy 2 led to a considerable variability for estimating daily evapotranspiration which was explained by the effect of the spatial variability due to the daily site sampling for the top soil layers (0 to 0.2 m). Strategy 3 appeared to be the best practical compromise between practical field considerations and the necessity to obtain accurate evapotranspiration measurements. The accuracy of daily evapotranspiration could reach ± 0.5 mm d^{-1}, and could be further improved by increasing the number of measurement sites. The best results were obtained with strategy 4, although such a destructive and time-consuming strategy is not likely to be practical.

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The estimation of evapotranspiration under natural conditions at different space scales (local, field, regional), and time steps (instantaneous, daily, seasonal) is crucial for water conservation and management, in particular planning the efficiency of irrigation and plant water use (Stone et al. 1973; Molz 1981), or field validation of water transport models (Camillo et al. 1983; Witono and Bruckler 1989). Available methods for measuring evapotranspiration are based on soil water balance estimation (Daudet and Vachaud 1977; Vachaud et al. 1978), direct measurements using lysimeters, micrometeorological methods, including portable chambers, eddy correlation or Bowen ratio (Perrier et al. 1975; Reicosky and Peters 1977; Itier 1981; Pal Arya 1988), or plant physiological methods (Sakuratani 1981; Valancogne and Nasr 1989). But none of these methods of measuring evapotranspiration is applicable under all conditions (Sharma 1985). The plant physiological methods based upon sap flow

measurements relate to a single plant and only measure transpiration, the soil water balance measurements provide local estimates of evapotranspiration, whereas the micrometeorological methods refer to field or regional scales for continuous and homogeneous crops.

When applied at a field scale, the major drawback of the soil water balance method is that it lacks sensitivity to measure daily evapotranspiration values, and that it is sensitive to the spatial variability of the soil, and thus to the sampling strategy (Peyremorte et al. 1972; Dunin and Aston 1981; Rambal et al. 1984; Vauclin et al. 1984). Numerous experimental data on the spatial variability of the soil water content have been published (Nielsen et al. 1973; Gajem et al. 1981). However, estimation of the spatial variability of actual evapotranspiration are rare, although such data are crucial for the development of stochastic water transport models. This work evaluated the effect of soil sampling strategies and measurement methods (neutron probe measurements and/or destructive mass based soil samples) on the estimation of the daily and cumulative evapotranspiration, and to quantify the spatial variability of evapotranspiration at field scale when soil water balance methods are used. To do this, water content and deep flux variations in space (field scale) and time (daily scale) were simulated, according to observed statistical properties of daily water content and the water flux at the bottom of the soil profile measurements of a field experiment. Different sampling strategies were then simulated and their effects on daily and seasonal cumulative evapotranspiration were quantified.

Simulation procedure for the soil water balance variability

Objectives and procedure

The purpose of the proposed procedure was to simulate a realistic spatial variability of daily water contents and deep fluxes (at 1.55 m), for estimating the evapotranspiration at field scale and its accuracy according to different sampling strategies. Every day, the distributions of the daily water content profiles and the flux at 1.55 m (qz_{max}) were generated at 1000 theoretical sites according to a statistical procedure. This procedure assumed that:

i) Experimental mean and variance of water contents and water fluxes were unbiased estimates of the true mean and variance at the field scale.

ii) The variability of data was isotropic and spatially independent, and could be described by a normal distribution. The variability of soil data may be such that the isotropic and random assumption are not valid, and the magnitude of the error with the assumption of randomness as opposed to some trends in the variation that is related to soil properties should be separated. Nevertheless, in our case, data collected on the same site (Bertuzzi et al. 1987) showed that at all depths in the 0.00–0.20 m soil layer, the histogram of dry bulk density was normally distributed and the experimental semivariogram did not show any trend (pure nugget effect). Moreover, results with gravimetric water contents measured in the 0.00–0.20 m soil layer were similar, and purely random distributions of water contents were observed.

For the water content at each depth, and the deep flux (qz_{max}), the simulation procedure started with the sampling of 1000 probabilities [p(i)] distributed on the unit normal distribution. For each day, the mean (μ) and the standard deviation (s) were estimated from field data, and it was then possible to simulate the distribution of 1000 spatially distributed values [x(i)] using the relationship:

$$x(i) = p(i) \cdot s + \mu. \quad (1)$$

Moreover, for the water content profiles, we observed from experimental data that the drier series stayed drier and the wetter sites stayed wetter, i.e. the order of the sites (more or less dry or wet) was approximately maintained versus time (see below in the next section). This was taken into account in the statistical procedure, in that the same probability p(i) generated by the statistical computation was used every day at a given site to compute the distribution of water content whatever the depth. We applied the same procedure for the deep flux (qz_{max}). This maintained the physical coherence observed on daily field data, i.e. the drier sites at the start of the procedure stayed drier and the wetter sites stayed wetter.

The soil water balance could then theoretically be calculated at each theoretical site. Thus, for the 3000 m^2 field, it was assumed that each was representative of the soil water balance of a 3 m^2 soil surface. Nevertheless, such theoretical work could be applied whatever the space scale and time step. The mean water balance components calculated on 1000 points were considered as a 'reference', i.e., the 'true' value of the water balance components. Data sets coming from different sampling strategies in the simulation were then sampled and compared to this theoretical 'reference', to finally compare their relative performances.

Comparing four sampling strategies

The characteristics of the four sampling strategies are indicated below

i) Strategy 1 used ten theoretical sites randomly located in the field. The daily water content estimates, and deep water fluxes, were assumed to come every day from these same ten location (neutron probe measurements for example). The first estimate began at 0.15 m, and the others were located every 0.10 m until 1.55 m (0.25; 0.35; 0.45; 0.55; 0.65; 0.75; 0.85; 0.95; 1.05; 1.15; 1.25; 1.35; 1.45; 1.55 m).

ii) Strategy 2 assumed that daily water content estimates combined data of two origins: in the 0.00–0.20 m soil layer, ten theoretical sites were selected for soil moisture estimates, but these theoretical sites changed every day (destructive soil samples for example). In the 0.20–1.60 m soil layer, 10 theoretical locations were also selected, but the daily water content estimates and deep water fluxes, were assumed to come every day from these same ten locations (neutron probe measurements for example).

The water content estimates in the 0.00–0.20 m layer used soil moisture of nine soil layers: 0.00–0.01, 0.01–0.02, 0.02–0.03, 0.03–0.04, 0.04–0.05, 0.05–0.07, 0.07–0.10, 0.10–0.15, 0.15–0.20 m. For the 0.20–1.60 m soil layer the first soil moisture estimated was located at 0.25 m, and the other were located every 0.10 m until 1.55 m.

iii) Strategy 3 used ten theoretical sites located in the field, as strategy 1. Water content estimates in the 0.00–0.20 m soil layer were assumed to come from accurate and non-destructive water content measurements (using capacitive probes or Time Domain Reflectrometry measurements for example). Thus, the estimation of water storage in the 0.00–0.20 m soil layer was from soil moisture estimates of nine soil layers: 0.00–0.01, 0.01–0.02, 0.02–0.03, 0.03–0.04, 0.04–0.05, 0.05–0.07, 0.07–0.10, 0.10–0.15, 0.15–0.20 m. For the 0.20–1.60 m soil layer, the first soil moisture estimate was located at 0.25 m, and the other were located every 0.10 m until 1.55 m (similar to those of strategies 1 and 2).

iv) Strategy 4 used 10 new theoretical locations of measurement evey day (destructive soil samples from the soil surface to 1.55 m for example). Precise water content estimates for thin layers were assumed to be available in the 0.00–0.20 m soil layer as in strategy 2. The layers for water content estimates in the 0.20–1.60 m were similar to those of strategies 1, 2, 3, i.e. every 0.1 m, starting at 0.25 m.

For these four strategies, the sites were sequentially selected randomly and the procedure prevented the same site being selected more than once.

Materials and methods

Test site

The field experiment was conducted at the Soil Science Laboratory of the Institut National de la Recherche Agronomique (INRA) at Montfavet (France) from July to the beginning of October 1989. Fifty-two soil samples (0–0.2 m depth) were taken on a hexagonal grid (0.3 ha) to evaluate the spatial variability of the particle size distribution. The soil is a clay loam with about 27% clay and 62% silt and the standard deviation for particle size classes is between 0.9 and 1.2% (Table 1), and thus the top soil layers of the field were regarded as 'homogeneous'. Clay contents were approximately constant until 0.6 m, and then increased (Table 2). No quantitative data about spatial variability of particle size distribution below 0.2 km were available, but field observations showed that spatial variability was low until 0.8 m in depth and increased after 0.8 m. The experimental field was subdivided into three subplots (Fig. 1). Soybean (*Glycine max*, (L.), cv "Weber") was sown on 3 July in rows 0.30 m apart on each subplot, and harvested on 4 October. Data were collected from Day 16 until Day 93 after sowing. The three subplots were irrigated with a sprinkle irrigation equipment (approximately 7 mm h^{-1}) on 23 (77.5 mm) and 30 (57.5 mm) July, and on 12 (45.5 mm) and 31 (17 mm) August. It rained on 14 August (2.6 mm), and on 8 (1 mm), 10 (35 mm), 13 (1.6 mm), and 18 (1 mm) September. The total water supply (rainfall and irrigation) was 238.7 mm, of which 17.3% was accounted for by rainfall.

Soil and crop measurements

Measurements combining the use of neutron probe and tensiometers were made at four sites on subplot B (Fig. 1). Each site was equipped with an aluminium access tube (length 2.0 m) surrounded with 15 tensiometers (mercury manometers) which were arranged in a circle of 1 m diameter around the access tube. The neutron probe (model SOLO 40) an the tensiometers (model DTM 5000, 15 mm in external diameter, 900 mb in maximum bubbling pressure) were manufactured by NARDEUX (Saint Avertin, France). Tensiometer measurements were made at 0.5 m, 0.10 m and every 0.10 m from 0.15 to 1.55 m below the soil surface. Neutron probe measurements were made at the same depths except the first two depths (0.05 m, 0.10 m). Measurements were made between 10.00 h and 12.00 h GMT every day until Day 75 after sowing, then at increasing time

Table 1. Basic statistics of particle size distribution (clay, fine silt, coarse silt, sand, and organic matter) for the 0.00–0.20 m soil layer, over a 0.3 ha field (52 locations)

	Clay (%)	Fine silt (%)	Coarse silt (%)	Sand (%)	OM (%)
Minimum	25.1	43.8	13.8	9.0	1.6
Maximum	29.6	48.3	17.8	13.1	1.9
Mean	27.2	45.9	15.8	11.0	1.7
SD	1.1	1.1	0.9	0.9	0.3
CV	4.0	2.6	5.6	8.3	4.7

OM: organic matter
SD: standard deviation
CV: coefficient of variation (%)

Table 2. Mean particle size distribution (clay, fine sild, coarse silt, sand) for the 0.00–1.6 m soil layer, over the 0.3 ha field

Depth (m)	Clay (%)	Fine silt (%)	Coarse silt (%)	Sand (%)
0.0–0.2	27.2	45.9	15.8	11.0
0.2–0.4	24.3	46.1	17.4	12.2
0.4–0.6	25.5	43.4	17.7	13.4
0.6–0.8	28.9	34.5	15.3	21.3
0.8–1.0	36.8	30.7	9.7	22.8
1.0–1.2	30.5	21.2	8.3	40.0
1.2–1.4	33.8	23.0	7.2	36.0
1.4–1.6	35.5	30.0	10.7	23.8

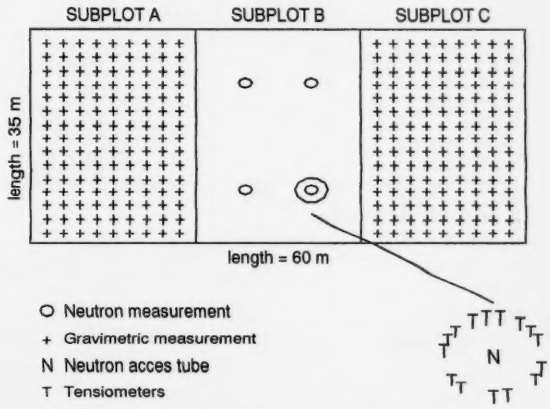

Fig. 1. The experimental setup

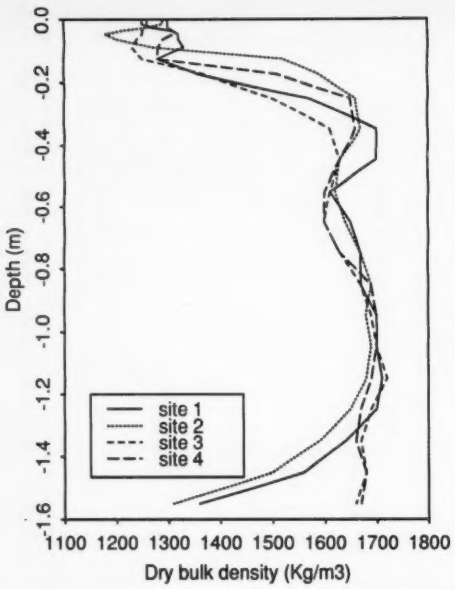

Fig. 2. Experimental dry bulk density profiles (sites 1 to 4)

interals from two to five days until harvest. Near the neutron sites, a gamma-ray transmission probe was used for bulk density measurements of the 0.00–0.20 m soil layer (Bertuzzi et al. 1987), and a retrodiffusion gamma ray probe manufactured by NARDEUX (Saint Avertin, France) for the 0.20–1.60 m soil layer, using the same access tubes as for the neutron probe measurements. Dry bulk densities varied approximately from 1200 kg m^{-3} to 1700 kg m^{-3} (Fig. 2) between the soil surface and the subsoil. The spatial variability between the four locations was rather high, especially in the top [0–0.25 m] soil layers and this may be due to previous wheel track compaction, as well as the tillage effects. Field observations showed that the depth of tillage could vary from 0.12 m to 0.22 m, and therefore the variability in the top soil layers was partly due to variations in the thickness of the tillage layer. The variability was also high at the bottom of the soil profile (1.30 to 1.60 m), and soil sampling with auger showed that it was probably due to variations in soil texture.

The neutron probe was calibrated in the field at the beginning of the experiment and during the observation period (347 data pairs of count rates and volumetric water contents were collected). Calibration was made using the corresponding dry bulk densitiy profile measured at each site to compute the volumetric water content. Different calibration relationships were grouped into account for three soil layers, 0.15 m, 0.25–0.85 m, and 0.95–1.55 m (Table 3). Thus, the residual standard deviation varied from 0.016 m^3 m^{-3} to 0.018 m^3 m^{-3}. Concurrently with neutron probe and tensiometer measurements in subplot B, gravimetric cores using an auger was taken on subplots A and C to characterize every day more precisely

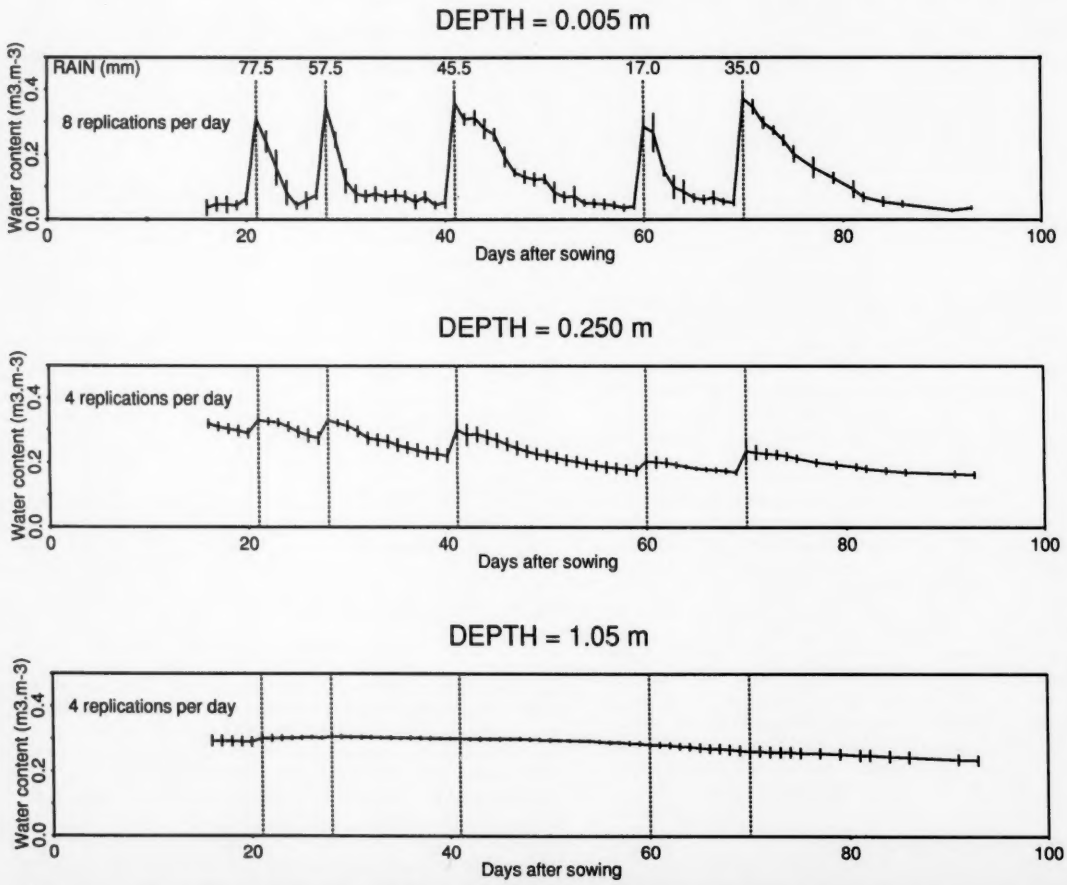

Fig. 3. Mean values and standard deviations of the volumetric water content at three selected depths (0.005 m, 0.250 m, 1.050 m)

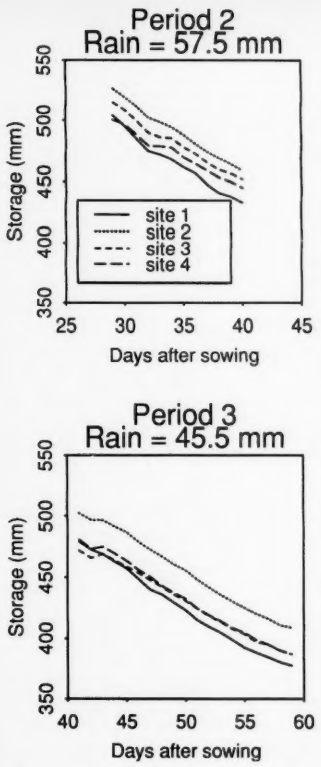

Fig. 4. Measured water storage at four sites versus time (Period 2: from day 28 to day 40 after sowing, Period 3: from day 41 to day 59 after sowing)

Table 3. Fitted parameters of the calibration of the neutron probe for 3 soil layers (0.00–0.15, 0.25–0.85, 0.95–1.55 m) and for the whole soil profile (0.00–1.55 m)

Depth (m)	n	a	b	r	SD ($m^3\ m^{-3}$)
0.00–0.15	32	0.00075	−0.0067	0.902	0.018
0.25–0.85	194	0.00085	−0.0509	0.883	0.019
0.95–1.55	121	0.00087	0.0745	0.812	0.016
0.00–1.55	347	0.00076	−0.0182	0.888	0.020

n: number of data
a: slope of the regression line
b: intercept of the regression line
r: coefficient of correlation
SD: standard deviation ($m^3\ m^{-3}$)

the contribution of near-surface soil layers to water storage variations. At eight randomly selected locations, nine core samples were taken at predefined depths (0.00–0.01, 0.01–0.02, 0.02–0.03, 0.03–0.04, 0.04–0.05, 0.05–0.07, 0.07–0.10, 0.10–0.15, and 0.15–0.20 m) to determine the gravimetric water content by oven-drying for 24 h at 105 °C. The corresponding volumetric water content was calculated by using the mean dry bulk density profile (from 0 to 0.20 m). Root distribution and depth were evaluated using the profile wall method (Tardieu, 1988). One to four vertical soil profiles (0.30 m in width) were exposed mechanically and soil carefully removed every week or more to expose roots visible at the wall of the profile. Roots present were recorded with a 0.02 m square grid. Observations were always made at a depth between the soil surface and the maximum visible root depth.

Figure 3 shows the variation of the volumetric water content versus time for three selected depths (0.005 m, 0.250 m, 1.050 m). The first depth (0.005 m) corresponds to destructive soil samples (8 samples per day), whereas the last two depths (0.250 m and 1.050 m) correspond to water contents derived from the neutron probe measurements. The order of magnitude of the standard deviation was approximately between 0.01 and 0.06 $m^3\ m^{-3}$. Standard deviations were greater for the top soil layer (0.005 m), where water supply and/or evaporation processes generally induced a high spatial variability. Moreover, the variability of water content with time could not be considered constant, but as dependent on water supply events (rain or irrigation). For deeper layers, 1.050 m for example, water content variability was low until approximately 55 days after sowing, and increased after 55–72 days after sowing as root growth, which was irregular in the field, induced a more or less rapid water depletion in the deeper soil layers.

Figure 4 showed the measured water storages at the four sites versus time for period 2: from day 28 to day 40 after sowing: and period 3: from day 41 to day 59 after sowing. Two periods were selected in Fig. 4, but similar results were obtained for all the experimental periods. Figure 4 indicated that the drier sites stayed drier and the wetter sites stayed wetter, i.e. the order of the sites (more or less dry or wet) was approximately maintained with time. As indicated, this experimental fact was taken into account in the statistical procedure, in that the same probability p(i) generated by the statistical computation was used every day at a given site to compute the distribution of water content whatever the depth, and this maintained the physical coherence because the drier sites at the start of the procedure stayed drier and the wetter sites stayed wetter. Similar results obtained under trickle irrigation were presented by Rolston et al. (1991).

Water balance estimates

When the soil tensiometric profiles showed a zero flux plane z_0 below the maximum root depth, evapotranspiration was calculated from the water storage variations between the soil surface and the zero flux plane z_0 (Vachaud et al. 1978). When zero flux plane was no longer visible on the soil tensiometric profiles, evapotranspiration was calculated from the water storage variations between the soil surface and a soil depth ($z_{max} = 1.55$ m) below the maximum root depth, and from the estimated water flux at this given depth (z_{max}), depending on water potential gradients and unsaturated hydraulic conductivity. Due to the development of the root system (Fig. 5), the zero flux plane was always located under root depth, from the beginning of the experiments to days 71, 60, 59, and 71 after sowing for sites 1 to 4, respectively. After these dates, the position of the zero flux plane for each site was unknown, because it was deepeer than the deepest tensiometer, maximum depth 1.55 m.

The unsaturated hydraulic conductivity – volumetric water content relationship in the bottom of the soil profile (1.55 m) was given by Van Genuchten (1980) according to Mualem's model (Mualem 1976):

$$K(\theta) = K_{sat} \cdot [\Theta]^{1/2} \cdot [1 - [1 - [\Theta]^{1/m}]^m]^2 \quad (2)$$

with

$\Theta = [\theta - \theta_r]/[\theta_s - \theta_r]$ (dimensionless)
K_{sat}: Saturated hydraulic conductivity ($m\ s^{-1}$)
θ_s: Saturated volumetric water content ($m^3\ m^{-3}$)
θ_r: Residual volumetric water contents ($m^3\ m^{-3}$)
m: Fitting parameter,

where the terms θ_s, θ_r and m come from the water potential – volumetric water content relationship (Van Genuchten, 1980) given by:

$$\psi(\theta) = 1/a \cdot [[\Theta]^{-1/m} - 1]^{1/n} \quad (3)$$

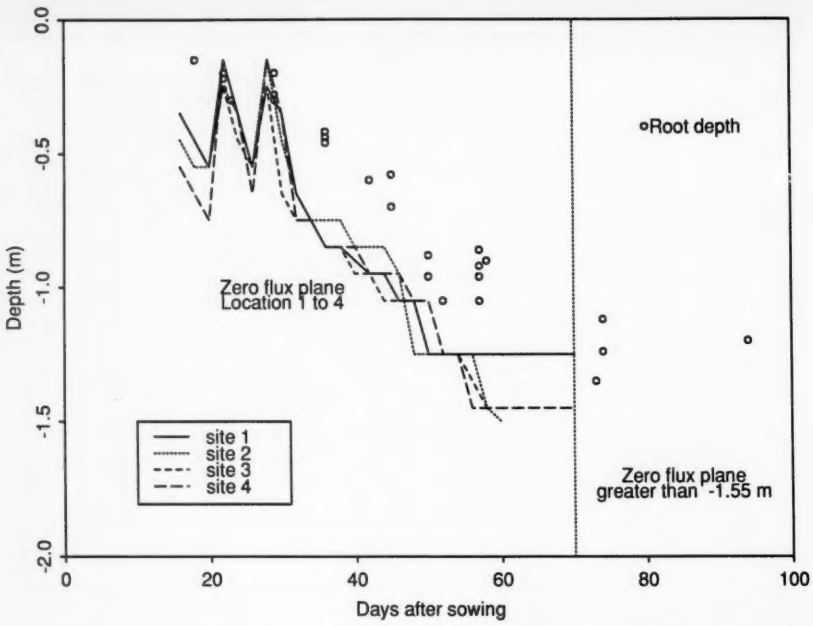

Fig. 5. Zero flux plane location and root depth versus time (four sites)

with

$m = 1 - 1/n$

n, a: Fitting parameters.

The parameters θ_s, θ_r, n, a were obtained by fitting Eq. (3) using water potential-volumetric water content data at depth z_{max} (Table 4). The procedure for estimating the unsaturated hydraulic conductivity-volumetric water content relationship then used tensiometric and neutron probe water content data. For the days when a zero flux plane z_0 existed, the unsaturated hydraulic conductivity-water content relationship [$K(\theta)$] was estimated using a non-linear procedure (Bard 1974) by optimizing the term K_{sat} of the $K(\theta)$ curve (Eq. (2)) to verify the equation [4], given as follow:

$$[S(z_0, z_{max})_{j+1} - S(z_0, z_{max})_j]/\Delta t_{j,j+1} = -K(\theta)z_{max} \cdot [(\delta\psi/\delta z)z_{max} - 1] \quad (4)$$

with

$S(z_0, z_{max})_{j+1}$: Water storage from z_0 to z_{max} at time j+1 (m)
$S(z_0, z_{max})_j$: Water storage from z_0 to z_{max} at time j (m)
$\Delta t_{j,j+1}$: Time step from time j to time j+1 (s)
$K(\theta)$: unsaturated hydraulic conductivity (m s^{-1})
ψ: water potential (m)
z: depth (m).

The terms $S(z_0, z_{max})_{j+1}$ and $S(z_0, z_{max})_j$ were derived from neutron probe measurements, and the water potential gradients $(\delta\psi/\delta z)z_{max}$ from tensiometric data. Thus, only the term K_{sat} was to be estimated when the water balance between z_0 and z_{max} had been established (Table 4), and once the $K(\theta)$ relationship was identified, the daily evapotranspiration could be estimated when the zero flux plane was no longer available. The functional relationships that express conductivity as a function of water content and the water potential as a function of water content do not account for hysteresis. Moreover, based on the variation of the bulk density as measured with the gamma probe, there should be significant differences in hydrodynamic properties between the four experimental locations. Thus, Table 4 indicates that different K_{sat} values were estimated for each location. The spatial variability for the parameter K_{sat} between the four locations was high (mean of 2.31 10^{-7} m s^{-1}, standard deviation of 2.45 10^{-7} m s^{-1}). The calculated water fluxes at the bottom of the root zone, and daily evapotranspiration for the four sites showed great variations between days (Fig. 6). Positive fluxes at 1.55 m corresponded to downward fluxes (drainage), whereas negative fluxes corresponded to upward flux (capillary raise). Spatial variability on daily evapotranspiration was essentially due to the spatial variability of the soil water content in the soil layers, and to measurement errors coming from neutron probe measurements. Residual standard deviation of the calibration relationships could have a not negligible effect on evapotranspiration estimates, when standard deviation is expressed as a fraction of daily evapotranspiration. For example, an error of 0.010 m^3 m^{-3} for a soil layer of 0.1 m depth corresponds to an error of 1 mm in evapotranspiration. Thus, errors from soil moisture measurement may result in the estimated actual evapotranspiration being greater than the potential evaporation. On the other hand, calculations showed that accuracy of weighting in the gravimetric method induced relative errors in gravimetric water content of less than 0.2%. Thus, errors in gravimetric measurements were considered as negligible. As a matter of fact, water storage calculations for the 0.00–0.20 m soil layer between two consecutive days varied greatly from

Table 4. Fitted parameters for the water potential-water content and for the hydraulic conductivity-water content relationships at four sites

Site	1	2	3	4
Water content – water potential relationship				
θ_s (m^3 m^{-3})	0.392	0.418	0.341	0.320
θ_r (m^3 m^{-3})	0.231	0.063	0.142	0.258
a (m^{-1})	0.727	1.013	0.825	0.296
n	1.752	1.192	1.143	1.135
Water content – hydraulic conductivity relationship				
K_{sat} (10^{-7} m s^{-1})	0.39	5.39	3.19	0.28
Mean (10^{-7} m s^{-1})		2.31		
Standard deviation (10^{-7} m s^{-1})		2.45		

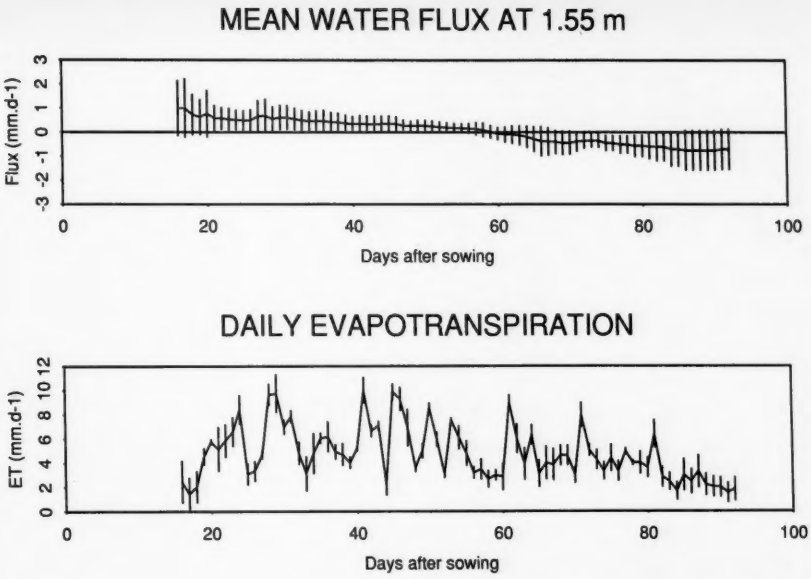
MEAN WATER FLUX AT 1.55 m
Flux (mm.d-1)
-3 -2 -1 0 1 2 3
0 20 40 60 80 100
Days after sowing
DAILY EVAPOTRANSPIRATION
ET (mm.d-1)
0 2 4 6 8 10 12
0 20 40 60 80 100
Days after sowing

Fig. 6. The experimental downward and upward fluxes at 1.55 m and the experimental daily evapotranspiration versus time

one day to another, depending on soil moisture sampling. Water fluxes at 1.55 m depth showed great variability between sites for both downward and upward fluxes (Fig. 6), and the mean flux varied approximately from +1 to −1 mm d^{-1} during the experiment.

Results and discussion

Comparing the four strategies

An example of the estimated variability of simulated water contents, water fluxes at 1.55 m and daily evapotranspiration at the field scale is shown in Fig. 7. Here spatial variability in water contents (0.28 m^3 m^{-3} to 0.36 m^3 m^{-3}), and water fluxes at the bottom of the soil profile (−0.08 to 1.06 mm d^{-1} at 1.55 m) resulted in a variability in the evapotranspiration (from 7.63 to 9.84 mm d^{-1}) which was not negligible. In Fig. 8 and 9, daily and cumulative evapotranspiration values according to strategies 1 to 4 compared to the reference daily and cumulative evapotranspiration. Daily evapotranspirations according to the four strategies are statistically compared to reference daily evapotranspirations in Fig. 10, where the solid line represents a slope do unity, and the dotted line the regression line fitted to the data:

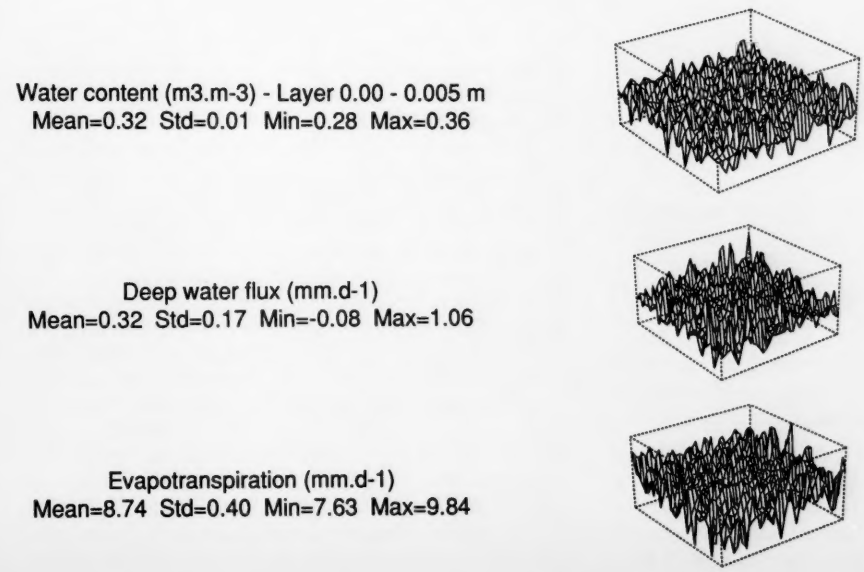
Water content (m3.m-3) - Layer 0.00 - 0.005 m
Mean=0.32 Std=0.01 Min=0.28 Max=0.36
Deep water flux (mm.d-1)
Mean=0.32 Std=0.17 Min=-0.08 Max=1.06
Evapotranspiration (mm.d-1)
Mean=8.74 Std=0.40 Min=7.63 Max=9.84

Fig. 7. Example of simulated volumetric water contents, deep water fluxes, and daily evapotranspiration on a grid layout of 1000 sites

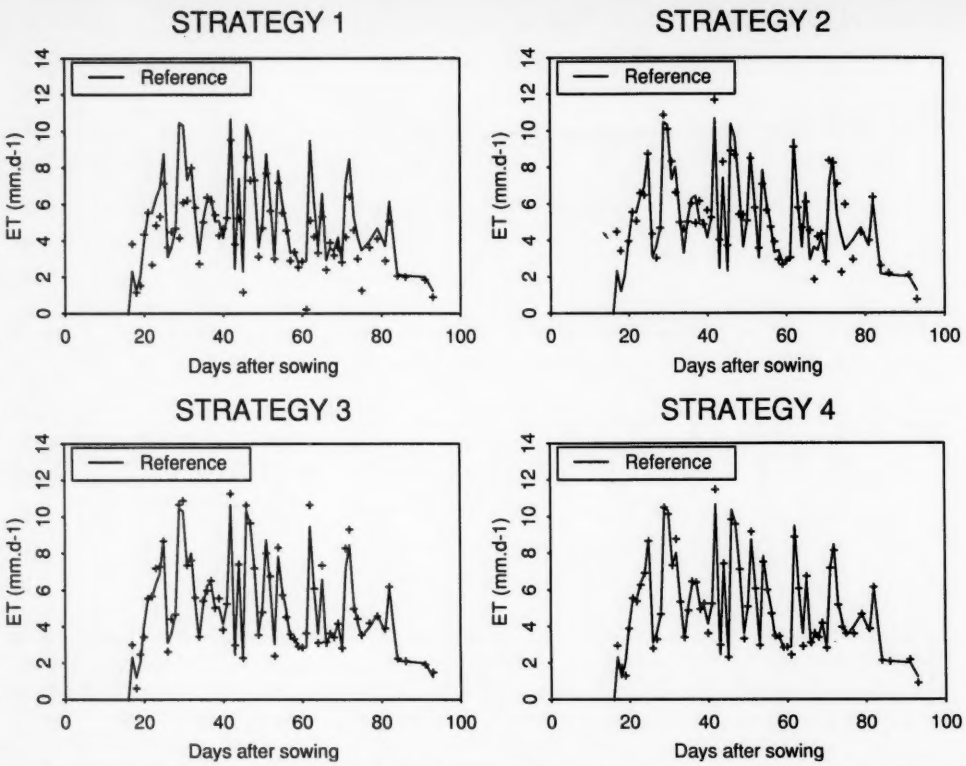

Fig. 8. Comparison between the mean simulated daily evapotranspiration (reference from 1000 sites) and the estimated daily evapotranspiration using four different sampling strategies

– Strategy 1 gave the worst results, because variations in the water content of the top soil layers were neglected, and thus the daily evapotranspiration was underestimated (Fig. 8). For example, evaporation after moderate rewetting of the top soil layers cannot be taken into account using this strategy.

– Strategy 2 gave a quite high variability for estimating daily evapotranspiration and gave less satisfactory results than strategy 3. This was explained by the effect of the spatial variability due to the daily site sampling for the top soil layers (0 to 0.2 m) resulting from the gravimetric method.

– Strategy 3 appeared to be the best practical compromise between restrictions in the field and the necessity to obtain accurate evapotranspiration measurements. Nevertheless, it would require the use of automatic sensors for soil moisture measurements in the top soil layer which have a fine vertical resolution such as capacitive probes. The accuracy of daily evapotranspiration could reach ± 1.0 mm d^{-1}, and this could be increased further by increasing in the number of measurement sites.

– The best results were obtained with strategy 4. In terms of the theory, this strategy simply means increasing the sample population, which in turn should increase the accuracy of estimation. Nevertheless, such a strategy is not likely in practical cases: Given the methods of field water content measurement now available this strategy will be very destructive and time-consuming.

Influence of the number of sites

In the case of strategy 3, the effect of the number of sites on the mean daily or cumulative evapotranspiration is shown on Fig. 11. The daily evapotranspiration was determined at field scale with an increasing number of sites: 3, 5, 20, 50, 100, 250, 500, 1000 where the soil water balance was calculated every day. Sites were selected randomly and added to the sites selected at the previous step. Ratios between simulated mean evapotranspirations and the corresponding reference values were computed every day for daily and cumulative evapotranspiration. The challenge here is determining the minimum number of samples that will give a reasonable answer from the practical standpoint, as increasing the number of values in the average will always improve the average. Under our field conditions and assuming that the range 0.90–1.10 for the ratio between simulated mean evapotranspirations and the corresponding reference values was satisfactory, accurate estimates of daily evapotranspiration at field scale required a minimum number of about 30 sites. This number was smaller, about 10 sites, for cumulative evapotranspiration, which is less sensitive to spatial variability.

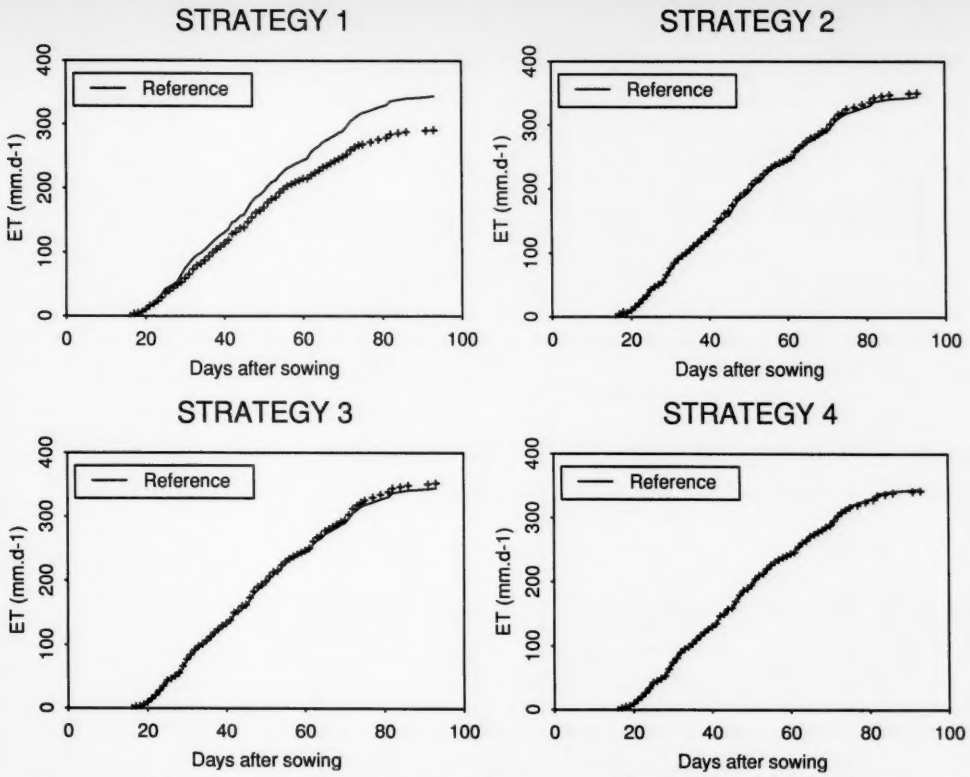

Fig. 9. Comparison between the mean simulated cumulative evapotranspiration (reference from 1000 sites) and the estimated cumulative evapotranspiration using four different sampling strategies

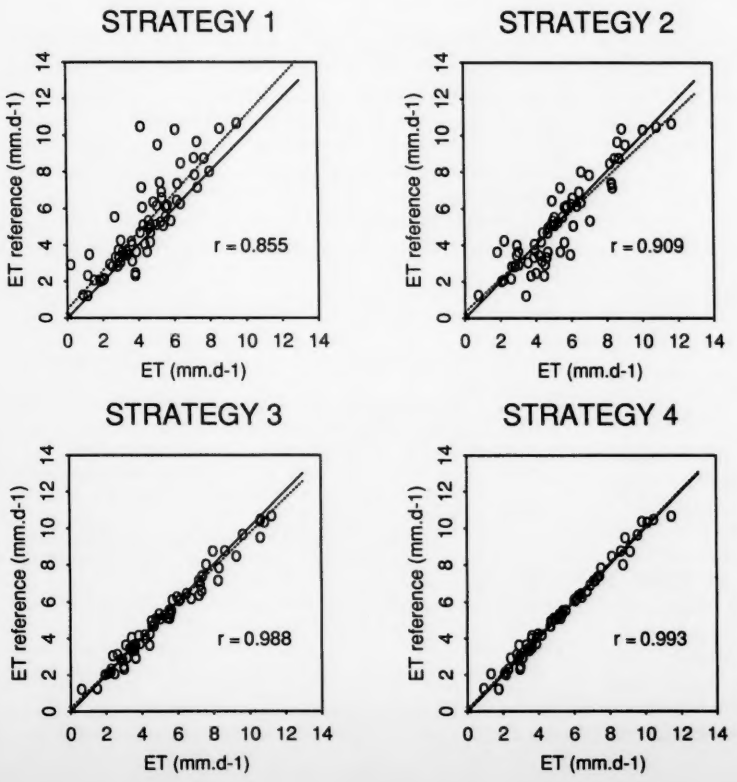

Fig. 10. Comparison between four sampling strategies to estimate the simulated daily evapotranspiration

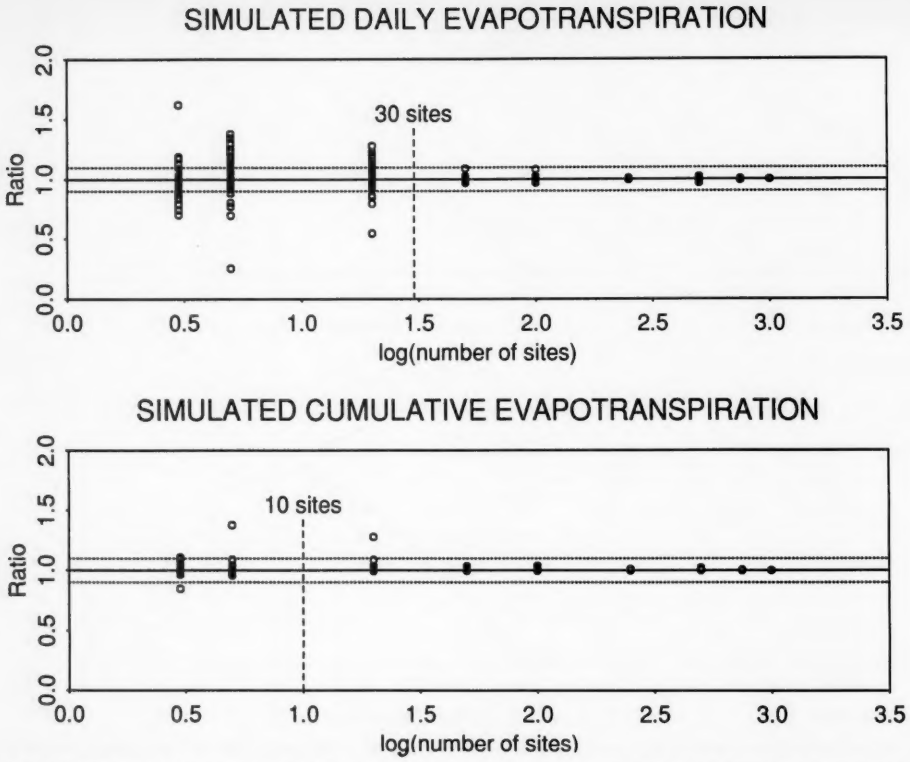

Fig. 11. Influence of the number of sites on the estimation of the simulated daily and cumulative evapotranspirations using strategy 3

These results confirm the fact that the determination at field scale of the daily actual evapotranspiration can be very inaccurate in the case where a limited number of measurement sites is used. Cumulative evapotranspiration estimates were less sensitive to the spatial variability of soil properties than the daily estimates.

Conclusions

A procedure for data simulation was established and performed to study, at a field scale, the effects of different sampling strategies on the actual daily and cumulative evapotranspiration. On the basis of realistic simulated data, this study shows that the spatial variability of the daily actual evapotranspiration is not negligible, even in small fields, 0.3 ha. Comparison of four soil moisture sampling strategies shows that a daily random sampling of sites provides the most accurate and unbiased daily evapotranspirations. Strategy that uses automatic sensors having a fine vertical resolution for soil moisture measurements in the top soil layers, such as capacitive probes, appeared to be the best practical compromise between field restrictions and the necessity to obtain accurate evapotranspiration measurements. In such a case, the accuracy of daily evapotranspiration could reach ± 1.0 mm d^{-1}, and could be further improved by increasing the number of measurement sites. These results were obtained assuming random spatial variability of the soil characteristics and it is necessary to extend them in the case of non-random spatial variability. The simulation procedure is able to provide a random field distribution of actual evapotranspirations. Simulation techniques, such as the turning band method, can be used to generate spatially correlated fields of evapotranspiration and then to compare the influences of various sampling strategies on the estimates of evapotranspiration at a field scale.

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Growth and yield responses of almond (*Prunus amygdalus*) to trickle irrigation

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Abstract. Growth and yield responses of developing almond trees (*Prunus amygdalus*, Ruby cultivar) to a range of trickle irrigation amounts were determined in 1985 through 1987 (the fifth through seventh year after planting) at the University of California's West Side Field Station in the semi-arid San Joaquin Valley. The treatments consisted of six levels of irrigation, ranging from 50 through 175% of the estimated crop evapotranspiration (ET_c), applied to a clean-cultivated orchard using a line source trickle irrigation system with 6 emitters per tree. ET_c was estimated as grass reference evapotranspiration (ET_o) times a crop coefficient with adjustments based upon shaded area of trees and period during the growing season. Differential irrigation experiments prior to 1984 on the trees used in this study significantly influenced the initial trunk cross-section area and canopy size in the 50% ET_c treatment and 125% ET_c treatment. In these cases, treatment effects must be identified as relative effects rather than absolute. The soil of the experimental field was a Panoche clay loam (nonacid, thermic, Typic Torriorthents). The mean increase in trunk cross-sectional area for the 3-year period was a positive linear function ($r^2 = 0.98$) of total amounts of applied water. With increases in water application above the 50% ET_c treatment, nut retention with respect to flower and fertile nut counts after flowering, was increased approximately 10%. In 1985 and 1987, the nut meat yields and mean kernel weights increased significantly with increasing water application from 50% to 150% ET_c. Particularly in the higher water application treatments, crop consumptive use was difficult to quantify due to uncertainty in estimates of deep percolation and soil water uptake. Maintenance of leaf water potentials higher than −2.3 MPa during early nut development (March through May) and greater than −2.5 MPa the remainder of the irrigation season (through August) were positively correlated with sustained higher vegetative growth rates and higher nut yields.

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Trickle irrigation of almond (*Prunus amygdalus*) orchards in California's San Joaquin Valley has increased significantly since the mid-1970's partly because of expected economic benefits related to improved water and nutrient use efficiency (Micke and Kester 1978; Fereres et al. 1981; Krauter 1985). However, the potential water conservation benefits have not generally been realized because research and field experiences have not developed the appropriate relationships between the trickle irrigation system, its operation, the soil hydraulic properties, and the irrigation requirement of almond. To further complicate concepts of appropriate trickle irrigation management for almonds, some of this expansion in planted areas has occurred in regions with heavier clay and clay loam soils in the western San Joaquin Valley rather than in the coarser-textured soils typical of much of the almond production area in the eastern San Joaquin Valley.

Spatial variation in soil water distribution due to differences in flow geometry and surface soil infiltration characteristics, combined with uncertainty in defining active root zones to monitor for water uptake, makes soil moisture-based irrigation scheduling difficult for many tree crops (Jury and Earl 1977; Fereres et al. 1981). In previous reports on the project described in this paper, Rolston et al. (1991) and Nightingale et al. (1991) discussed spatial variability of soil water distribution with respect to distance from the tree and trickle lateral. They described the very complicated wetting pattern and considerable potential for deep percolation losses and leaching with the line-source trickle system used in this experiment.

Increasing availability of weather stations and evaporation pans for meteorological-based evapotranspiration (ET) predictions may provide the basis for greater use of reference ET-based irrigation scheduling, provided accurate information is available to relate water use by developing crops to standard measures of reference ET (Aljibury et al. 1974; Doorenbos and Pruitt 1977; Fereres et al. 1981). Trickle irrigation systems are particularly well-suited to automated operation to apply some percentage of reference ET at any desired irrigation frequency.

Under advective conditions of an immature orchard, Fereres et al. (1981) demonstrated a nonlinear relationship between percent groundcover and percent of ET of a mature almond orchard (assumed to have 70% groundcover), while Aljibury et al. (1974) assumed a linear relationship. Fereres et al. (1981) concluded that the nonlinearity of this relationship was further accentuated by reduced soil evaporation and sensible heat transfer associated with bare, dry soil between tree rows under trickle irrigation, and developed a crop coefficient based upon percent ground cover for use with developing almond orchards.

As with many other species, almond tree responses to water deficits depend on the rate of water stress development, method of irrigation, and available soil water as influenced by root distribution, wetted soil volume, and soil water holding capacity (Castel and Fereres 1982; Ruiz-Sanchez et al. 1988). Almond studies under trickle irrigation have concentrated on tree responses to long periods (weeks, months) of complete cessation of irrigation (El-Sharkawi and El-Monayeri 1976; Castel and Fereres 1982; Krauter 1985). Tree responses to continuing, high frequency irrigation in amounts ranging from deficit to full ET are the focus of this study, and little information is available on almonds under these conditions.

This investigation reports the effects of the quantity of applied water, by a single-line source trickle irrigation system, on plant water status and selected growth and nut production parameters for almond grown in a clay loam soil. Tree responses are described in relation to applied water plus rainfall rather than a complete water balance. This study has focused on the early nut-bearing years (4 to 7 years after planting) for the Ruby cultivar.

Experimental procedures

The experimental field was at the University of California's West Side Field Station 9.6 km south of Five Points, California, on the west side of the San Joaquin Valley. The soil is a Panoche clay loam (nonacid thermic family of Typic Torriorthents) derived from recently deposited alluvium from calcareous sandstones and shales. Water retention properties within the tree root zone (upper 2 m of soil profile) are relatively uniform with depth (Nielsen et al. 1964), and the soil has a high plant-available water-holding capacity, averaging over 425 mm in a 2.5 m deep soil profile (Nielsen et al. 1973; Grimes et al. 1975).

The experiment utilized almond (*Prunus amygdalus*) trees planted in February 1980. The 3.4 ha orchard had 63 rows of trees, 14 trees per row. Tree spacing was a 6.1 by 6.1 m square pattern. Each treatment plot had 3 east-west-oriented rows of 7 trees each, 2 border rows (Butte cultivar) and a central experimental row of the Ruby cultivar. One tree at each end of a row within each plot and the two rows of Butte cultivar served as the border trees to the five experimental trees. Both cultivars were grafted to Nemaguard rootstock which has shown moderate to good late-season drought tolerance (Micke and Kester 1978; Micke and Kester 1988). The Ruby cultivar is a medium-size tree with moderate vigor, an upright growth habit, and a large number of spurs, and is classified as late blooming and late nut maturity relative to other California-adapted cultivars (Kester et al. 1985).

No weeds were allowed to develop within the orchard, resulting in a clean orchard floor for the duration of the experiment. The area immediately surrounding the orchard on three sides was in row-crop production (cotton, processing tomatoes, cantaloupe) and in the downwind direction was bordered by table grapes. During the high ET periods of each year (June through September), surrounding crops were not water-stressed and had leaf area indices ranging from a low of 2 in early June through 4 or more in July and August. Monthly grass reference ET and heat unit accumulation each year during the period from opening of new leaves in March through irrigation cutoff prior to nut harvest are shown in Table 1. The annual rainfall at the orchard for consecutive years was 136, 183, and 216 mm in 1985, 1986, and 1987. The long-term (15-year) average annual rainfall averages 140 mm.

Table 1. Monthly total reference evapotranspiration and accumulated heat units (base temperature 12 °C) in March through August of consecutive years at West Side Field Station near Five Points, CA

Month	Grass-reference evapotranspiration (mm)			Accumulated heat units (base 12 °C)		
	Year			Year		
	1985	1986	1987	1985	1986	1987
March	115	94	100	127[a]	118	70
April	187	151	174	198	146	214
May	210	216	192	226	269	281
June	219	234	214	379	361	346
July	236	218	241	436	401	428
August	210	207	228	370	386	437

[a] Heat units calculated based on daily average temperature (determined from daily maximum and minimum temperatures) minus a base temperature of 12 °C

A trickle irrigation experiment was initiated following the 1980 planting and until the end of 1983 had 6 treatment combinations (T1 through T6) coded W_1N_1, W_2N_1, W_3N_1, W_1N_2, W_2N_2, and W_3N_2, respectively. The treatment designations W_1, W_2, and W_3 corresponded to trickle irrigation levels of 67%, 100%, and 133% of a calculated crop evapotranspiration (ET_c), and N_1 and N_2 corresponded to either a single level of nitrogen (N) fertilizer applied in the fall after nut harvest (subscript 1) or the same total amount of N applied continuously in small increments during the growing season (subscript 2). In the spring of 1984, the original experiment was discontinued and the number of water application treatments was increased to the 6 levels of trickle irrigation considered in this paper (50, 75, 100, 125, 150, and 175% of the computed ET_c, designated with the new treatment codes T1, T2, T3, T4, T5, and T6, respectively). The original 6 treatments became, respectively, the new T2, T3, T6, T1, T4, and T5 treatments. The 1984 growing season was considered transitional and only limited observations from that year are reported. Tree trunk diameters were measured in December of 1983, just prior to the transition to the new irrigation treatments, in order to assess carry-over effects of old treatments on initial tree size. The experimental design was a randomized complete block, with six irrigation treatments and seven blocks.

The irrigation water was of relatively constant inorganic chemical composition, with a mean electrical conductivity (EC) of 1.54 dS m^{-1}, and 3-year mean B, Na^+, SO_4^{2-}, and Cl^- concentrations of 0.08, 8.3, 5.3, and 3.3 mol l^{-1}. One drip irrigation line was used for each row of 7 trees, with the line placed parallel to the tree row direction within 10 cm of the tree trunks. There were 3 emitters on both sides of each tree at distances of 0.5, 1.25, and 2.0 m from the tree, with emitters delivering 4, 8, and 8 l h^{-1}, respectively. The full daily irrigation amounts were applied during either one or two continuous application periods. One m^3 of water per tree was equivalent to a depth of 26.9 mm of water if applied uniformly over the 37.2 m^2 of land area allotted to each tree.

The 6 levels of irrigation used in 1984 through 1987 were based on percentages of the calculated crop evapotranspiration (ET_c)

requirement derived from a nearby (100 m distance) weather station (data processed to determine grass reference evapotranspiration, ET_0), and a crop factor based on the time of year and the percent of ground area shaded by the tree canopy (Micke and Kester 1978; Fereres et al. 1981).

The shaded area (measured between 11:30 and 12:45 h, Pacific Standard Time) was expressed as a percent of the plot ground area allocated to each tree (37.2 m^2) based on planting density. Shaded ground area was estimated according to the methods of Fereres et al. (1981) on three trees within each of four field replicates of a treatment by marking off the total 37.2 m^2 ground area per tree in sub-plots and classifying them as either shaded by tree leaves and branches or not shaded. Since treatment T3 was designated to receive irrigation to replace 100% of estimated ET_c, shaded ground area measurements of that treatment as a function of time were used in the calculation of ET_c. Treatment-specific shaded ground areas were not used in the ET_c calculations for other treatments. Irrigation volumes of other treatments (T1, T2, T4, T5, T6) were calculated to apply 50, 75, 125, 150, and 175% of ET_c calculated for treatment T3.

The temporal persistence of soil-water contents and associated soil water potential as a function of location within the root zone was investigated as part of this experiment by Rolston et al. (1991). Changes in soil water content were determined by neutron attenuation from 12 to 25 neutron access tubes per tree distributed across a wide range of positions on one side of trees in all treatments other than T5, and soil water potentials at specific locations were monitored using tensiometers, as discussed by Rolston et al. (1991). Their data from this experiment was used to calculate a soil water balance for treatment T3. This data was used to modify crop coefficients in 1986 and 1987.

The irrigation season was divided into two-week periods. For each two-week period, the mean daily required quantity of water to meet 100% of estimated ET_c was calculated. Post-harvest irrigations were applied in uniform amounts to all treatments during October and November of each year. No water was applied from December until the beginning of irrigation each spring.

Trees received liquid nitrogen-fertilization (urea, 28% N by weight) through the trickle line at a rate of 0.34 kg N $tree^{-1}$ just after harvest in 1985; 0.45 kg in 1986; 0.23 kg in May and 0.45 kg just after harvest in 1987. Early-summer (May) and mid-summer (July) leaf blade samples (50 leaves per plot) were analyzed for leaf blade N, P, K, Ca, Mg, Na, B, Cu, Mn, and Zn. The concentrations of these elements in all leaf samples were sufficient and not growth- or yield-limiting according to University of California guidelines (Micke and Kester 1978).

The trees were pruned annually to encourage new growth for sustained production of fruiting spurs, following University of California pruning guidelines (Micke and Kester 1978). The effects of irrigation practices on tree growth and canopy size were evaluated by measuring: trunk circumference at the same point each year after leaf abscission; scaffold branch diameter at a distance ranging from 20 to 30 cm of attachment to the primary trunk; tree shade area from March through mid-July. Branch diameter measurements were made on two primary scaffold branches per tree, three trees per treatment, in each of three blocks during 1986 and 1987.

Leaf water potentials (LWP) were determined with a pressure chamber (Soil Moisture Model 3000, Santa Barbara, CA) on fully-illuminated (photosynthetic photon flux density greater than 1400 μmoles m^{-2} s^{-1}) spur branch leaves collected from sites within 30 cm of branch tips. In preparation for measuring LWP, leaves were placed in plastic bags before excision. Water potentials were determined on four separate trees in three separate field blocks of each treatment. Leaf conductance to water vapor was determined on two fully-illuminated spur branch leaves on each of three trees in three field blocks of each treatment using a steady-state porometer (Li-Cor Model 1600, Lincoln, NE).

Nut retention, as a percent of the number of flowers counted during peak bloom, was determined 5 to 7 weeks after the rate of embryo abortion had significantly declined and initial fruit drop had subsided, and again just before harvest in all three years. These counts were made on marked 1 m long sections of branches, starting at the branch tip. Branches 1.5 to 2 m above the soil surface were measured in north, south, east and west quadrants of each of 12 trees per treatment.

Nut yields and nut characteristics for each irrigation treatment were based on 5 trees harvested in each of the 7 blocks per treatment. A modified commercial tree shaker, windrow and sweep were used for the harvest. A 5 to 7 kg random sample was collected from each plot to determine wet and air dry (45 C) weights, trash percentage, and shelling percentage. Average kernel weights were determined from three separate 100-kernel samples from each treatment block.

Single-degree-of-freedom orthogonal contrasts were used to determine irrigation treatment effects on growth and yield responses (SAS Institute 1985).

Results and discussion

Irrigation quantity

Applied water plus rainfall for the six irrigation treatments for 1985 through 1987 are shown in Table 2. Spring and summer trickle irrigation for the treatment designed to receive 100% of estimated ET_c (T3) increased from a total of 13.1 m^3 $tree^{-1}$ in 1985 to 19.2 m^3 $tree^{-1}$ in 1986 to 26.7 m^3 $tree^{-1}$ in 1987 due to modifications in the crop coefficient to account for both increases in tree canopy size and changes in the calculated soil water use.

Data in Fig. 1 illustrate the range of volumetric water content in the soil profile across several treatments at neutron access tube positions 1.5 m east of the instrumented trees in the trickle lateral direction and 1 m south of the lateral. Higher water applications associated with increases in tree shaded area in 1986 and 1987 and more winter rainfall than 1985 resulted in higher early- to mid-summer soil water contents with depth in all treatments than in 1985. In specific areas of the root zone, similar treatment differences in patterns of soil water content persisted during much of each year due to low annual rainfall and consistent treatment differences in applied water. Soils at the experiment site have been previously identified as having average volumetric water contents of about 0.35 and 0.13 at −0.03 MPa and −1.5 MPa soil matric potential, respectively (Nielsen et al. 1973; Sharples 1986).

Soil water depletion and deep percolation in this experiment were discussed by Nightingale et al. (1991) and Rolston et al. (1991). Rolston et al. (1991) described the 1986 soil water depletion between days 100 and 270 (just after harvest) as less than 2000 l $tree^{-1}$ and 3000 l $tree^{-1}$ in the 50% ET_c and 175% ET_c treatments, respectively. These amounts represent about 20% and less than 10% of the total applied water for the year in the 50% and 175% ET_c treatments, respectively. Season-total soil water use estimates were of similar magnitude in treatments measured in 1985 and 1987.

Fereres et al. (1981) procedure for calculating immature tree water use, which was used in this study, is based on ET_c rates determined under flood irrigation for mature trees with a correction based on the percent of shaded ground area. In flood irrigation the water is applied over a large ground area per tree, while the single

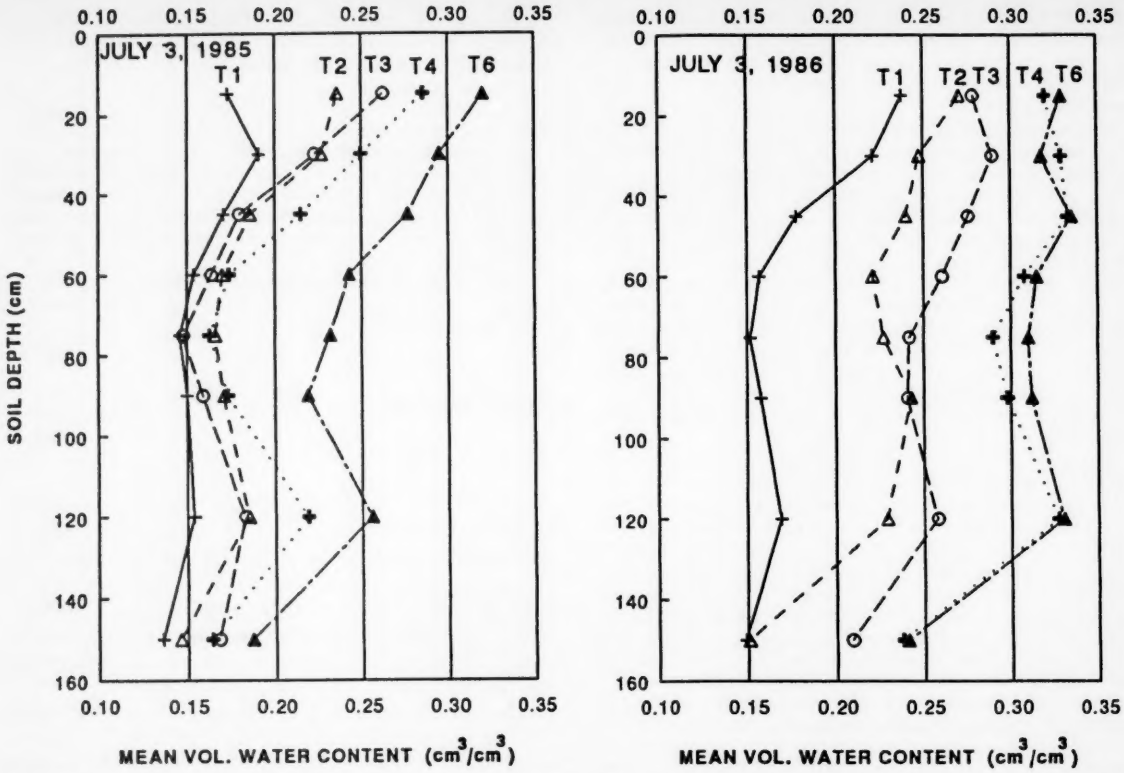

Fig. 1 a, b. Mean soil volumetric water content as a function of depth in the soil profile and irrigation treatment for trickle irrigated almonds in (**a**) July, 1985; and (**b**) July, 1986

Table 2. Rainfall and trickle-applied water as a function of irrigation treatment in 1985, 1986, 1987 for trickle irrigated almonds at the West Side Field Station near Five Points, CA

Treatment code	Irrigation rate (as % of ET_c)	Year					
		1985		1986		1987	
		Postharvest irrigation plus rain[a] (mm)	Main season irrigation[b] (mm)	Postharvest irrigation plus rain (mm)	Main season irrigation (mm)	Postharvest irrigation plus rain (mm)	Main season irrigation (mm)
T1	50	137	171	245	267	440	368
T2	75	136	261	245	395	431	546
T3	100	141	347	245	511	431	716
T4	125	140	441	241	647	414	897
T5	150	135	525	247	761	415	1085
T6	175	135	597	246	885	403	1258

[a] Irrigation water applied after the previous year's harvest (usually in October–November of previous year) plus rainfall through September harvest of the year shown; post-harvest irrigation amount averaged 70 mm, 85 mm, 159 mm in 1984–1985, 1985–1986, and 1986–1987, respectively

[b] Water applied between February and September of each year

trickle line per tree row in this study only resulted in wet surface areas extending 0.5 to 1.25 m beyond the trickle line location. The mismatch between the small infiltration area of the single trickle line per tree row and the relatively high water application rates could have resulted in considerable deep percolation losses, as suggested by Nightingale et al. (1991). The relative size of the wetted zone and infiltration area could be changed with modifications of emitter application rates and irrigation frequency (Jury and Earl 1977). Such modifications may be

Table 3. Almond tree trunk cross-sectional area determined from measured diameters as a function of irrigation treatment for the Ruby variety at the West Side Field Station in 1983 through 1987. Orthogonal comparisons are shown for major treatment comparisons

Irrigation treatment code	Mean trunk cross-sectional area[a] (cm^2)				
	Year				
	1983	1984	1985	1986	1987
T1	89.9	96.8	103.9	114.9	130.7
T2	100.3	111.2	116.9	134.8	153.9
T3	103.9	118.8	128.7	147.4	172.0
T4	113.1	138.9	156.1	179.1	206.1
T5	102.1	132.7	153.9	179.1	211.1
T6	103.9	136.8	165.1	193.6	226.9
Comparisons[b]					
T1 vs. T2	*	**	**	**	**
T1 vs. T3	**	**	**	**	**
T2 vs. T3	NS	*	**	*	*
T2 vs. T4	*	**	**	**	**
T3 vs. T4	NS	**	**	**	**
T3 vs. T5	NS	**	**	**	**
T3 vs. T6	NS	**	**	**	**
T4 vs. T5	NS	NS	NS	NS	NS
T4 vs. T6	NS	NS	NS	NS	NS
T5 vs. T6	NS	NS	NS	*	NS

[a] Mean of 35 trees (7 blocks, 5 per block) after fall leaf drop (between day 307 and day 337, depending on the year)
[b] Orthogonal comparisons within a year designated as NS, *, or ** were not significant, significant at the $P<0.10$ level, or significant at the $P<0.05$ level, respectively

worth considering in attempts to limit deep percolation losses and better match short-term water storage to crop water use.

Tree growth

Just prior to initiation of the 1984 treatments, trunk cross-sectional areas in December, 1983 were significantly smaller in new treatment T1 trees than in all other treatments (Table 3). During 1981 through 1983, treatment T1 was a low water application treatment (W_1N_2), and the smaller trunk cross-section area in December, 1983 indicated a carry-over effect of the prior treatment on the 1984 through 1987 treatment. Initial trunk cross-section area of treatment T4 was also significantly greater than T2, but not significantly different from other treatments. December 1983 trunk cross-section areas of the other treatments were not significantly different.

The long-term relative effect of specific treatments can be assessed by looking at the consistency of treatment effects relative to the 100% ET_c treatment (T3). The ratio of trunk cross-section areas of low water application treatments (T1, T2) to the 100% ET_c treatment (T3) generally declined from 1983 through 1987 (calculated from Table 3). The ratio for high water application treatments (T4 through T6) started near 1.0 to 1.1 in 1983 and increased to 1.2 to 1.3 in subsequent years. In treatments

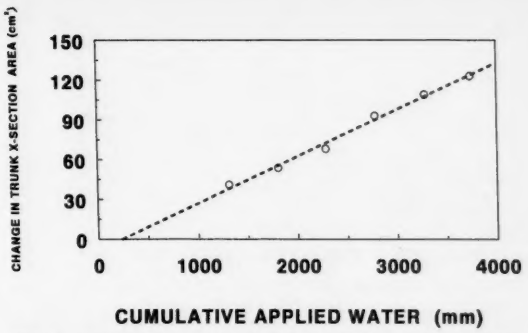

Fig. 2. Increase in trickle-irrigated almond tree trunk cross-sectional area of all irrigation treatments during the December, 1983 through December, 1987 period as a function of cumulative post-harvest plus irrigation season trickle-applied water. Linear regression equation: $y=0.035\,x-8.39$; $r^2=0.98$, $n=30$

T2 through T6, increases in trunk cross-section areas in 1984 through 1987 were roughly in proportion to applied water, and the ratio of treatment cross-section areas to treatment T3 areas were also positively correlated with applied water. The potential carry-over effects of the pre-1984 treatment cannot be separated from post-1984 responses in treatment T1.

Other than treatment T1, tree trunk cross-section areas in 1983 were not significantly affected by the pre-1984 nitrogen subtreatments within each irrigation level (data not shown). 1984 is a difficult year to assess in terms of treatment effects. Even though 1984 was described as transitional between the two experiments, treatments in 1984 were irrigated according to the same 50 to 175% ET_c rates scheduled for the 1985 through 1987 seasons. Trunk growth rates in 1984 were roughly proportional to applied water (Table 3).

As shown in Fig. 2, a linear relationship ($r^2=0.99$) was observed between the increase in trunk cross-sectional area from 1985 through 1987 and the total amount of irrigation water. Although this linear relationship implies a direct response to increases in applied water, it is probably related to a combination of factors including the increased wetted-soil volume created by the higher applied water volumes, increased root activity, and perhaps, access to more soil nutrients within a larger rooting volume.

Scaffold branch growth expressed as a mean increase in branch diameter for five two-month periods in 1987 is presented in Table 4. The highest rate of growth ($\mu m\ day^{-1}$) occurred from April 16 to June 3 for all irrigation treatments. As water stress intensified in mid-summer, branch growth rates declined more in treatments T1 and T2 than in higher water treatments.

The increases in shaded ground area during the three growing seasons are illustrated in Fig. 3 for the T3 (100% ET_c) treatment. The within-season changes in scaffold branch diameter were not linear, following a different seasonal pattern than changes in shaded area (Table 4, Fig. 3). Since shaded ground area as measured cannot distinguish between intensities of shading nor detect multiple layers of leaves, it is not necessarily a good estimate

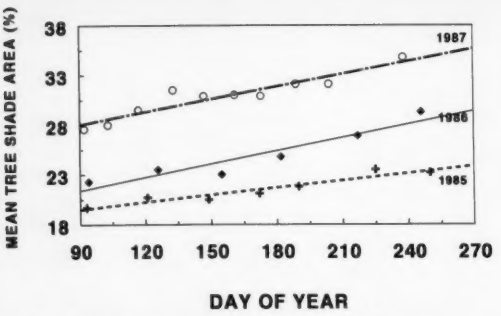

Fig. 3. Mean shaded ground area (expressed as percentage of total ground area of 37.16 m^2 per tree) of treatment T3 (100% ET_c) almond trees as a function of day of year in 1985, 1986, and 1987. Linear regression equations were as follows: (1985) $y=0.024x+17.4$, $r^2=0.91$, $n=18$; (1986) $y=0.045x+17.4$, $r^2=0.89$, $n=18$; (1987) $y=0.042x+24.3$, $r^2=0.88$, $n=18$

Table 4. Average daily increase in the diameter of the primary scaffold branches of almond trees as a function of trickle irrigation treatments for selected time periods in 1987

Date		Increase in mean diameter (μm day^{-1})					
From	To	Trickle irrigation treatments					
		T1	T2	T3	T4	T5	T6
Feb. 5	Apr. 16	<5[a] (2)	<5 (2)	<5 (2)	<5 (3)	<5 (2)	<5 (3)
Apr. 16	Jun. 3	44 (6)	52 (7)	46 (8)	47 (3)	48 (5)	59 (11)
Jun. 3	Aug. 12	13 (5)	30 (3)	42 (12)	43 (6)	47 (4)	53 (6)
Aug. 12	Sep. 28	2 (1)	9 (2)	17 (4)	15 (3)	17 (2)	19 (5)
Sep. 28	Dec. 18	<5 (1)	<5 (1)	<5 (2)	<5 (1)	<5 (1)	<5 (1)

[a] Mean of 2 primary scaffold branches per tree, 3 trees per treatment plot in each of Blocks 3, 4, and 5; $n=18$ per treatment for each measurement date; standard error of the mean shown in parentheses under the mean for each treatment and date

of within-season changes in total tree leaf area. Rather, it is more closely related to changes in canopy diameter.

Between April of 1984 and July of 1987, ground areas shaded by trees (as a percent of the 37.2 m^2 of land allocated each tree) changed from 16% to 23% in treatment T1, from 17% to 27% in T2, from 17% to 35% in T3, from 19% to 36% in T4, from 20 to 40% in T5, and from 18% to 41% in T6. The only significant difference in initial 1984 shaded ground areas was between T1 versus T4 and T5. As with trunk cross-section areas, the lower initial shaded ground area of treatment T1 indicated a significant carry-over effect of the 1980 through 1983 treatment.

Under the conditions of this experiment, significant leaf drop (resulting in more than a 5% reduction in tree shaded area) was not observed prior to the cessation of irrigation in any year even in the T1 or T2 treatments.

Table 5. Mean leaf water potential for each of the months of May, June, July and August of fully-illuminated spur branch almond leaves on the southwestern quadrant of trees within 30 cm of branch ends as a function of irrigation treatment in 1985, 1986, and 1987

Month of year	Irrigation treatment	Leaf water potential (MPa)					
		Year					
		1985		1986		1987	
		Mean[a]	S.E.[a]	Mean	S.E.	Mean	S.E.
May	T1	−2.58	0.05	−2.65	0.12	−2.61	0.10
	T2	−2.40	0.04	−2.53	0.08	−2.57	0.06
	T3	−2.17	0.08	−2.44	0.06	−2.39	0.03
	T4	−2.08	0.06	−2.34	0.09	−2.21	0.04
	T5	−2.02	0.02	−2.30	0.04	−2.09	0.07
	T6	−1.94	0.08	−2.31	0.06	−2.16	0.08
June	T1	−3.07	0.04	−2.69	0.08	−2.85	0.11
	T2	−2.96	0.09	−2.57	0.04	−2.69	0.05
	T3	−2.74	0.13	−2.47	0.05	−2.52	0.06
	T4	−2.51	0.11	−2.30	0.04	−2.34	0.05
	T5	−2.42	0.10	−2.25	0.04	−2.22	0.07
	T6	−2.43	0.07	−2.16	0.04	−2.17	0.06
July	T1	−3.12	0.06	−2.86	0.11	−2.92	0.12
	T2	−3.07	0.14	−2.71	0.03	−2.85	0.08
	T3	−2.68	0.09	−2.58	0.04	−2.59	0.05
	T4	−2.33	0.06	−2.46	0.09	−2.31	0.07
	T5	−2.22	0.10	−2.31	0.07	−2.19	0.04
	T6	−2.15	0.09	−2.27	0.13	−2.22	0.06
August	T1	−3.20	0.15	−2.81	0.08	−3.08	0.15
	T2	−3.02	0.06	−2.63	0.04	−2.89	0.12
	T3	−2.65	0.06	−2.42	0.09	−2.64	0.07
	T4	−2.35	0.06	−2.35	0.07	−2.49	0.02
	T5	−2.26	0.12	−2.29	0.11	−2.29	0.05
	T6	−2.21	0.08	−2.27	0.06	−2.33	0.05

[a] Mean and standard error of the mean (S.E.) for leaves sampled on from two to three separate days per month. On each treatment within each sample date, one spur branch leaf per tree on each of four separate trees was sampled in field blocks 3, 4, and 5; $n=12$ per treatment

However, at harvest (12 to 19 days after irrigation cutoff), leaf drop was significantly higher (25 to 40% of total leaves) in treatments T1 and T2 than in other treatments (<10% of total leaves).

Plant water status

Average leaf water potentials (LWP) of fully-illuminated leaves across irrigation treatments exhibited similar trends during each year of the study (Table 5). At water applications below the 150% ET_c level, LWP declined progressively (Table 5). LWP of treatments T5 and T6 were not significantly different on any measurement date during the entire study. March and April LWP values were higher than −2.5 MPa in all treatments (data not shown). Late-season (July, August) leaf water potentials were higher in treatments T1, T2 and T3 in 1986 than in the other two years. Average soil water contents of these treatments were 5 to 8% higher in late July and mid-August in 1986 than during similar periods in the other

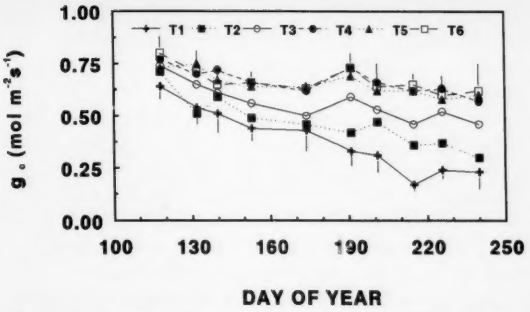

Fig. 4. Leaf conductance to water vapor (g_c) of fully-illuminated almond leaves as a function of day of year and irrigation treatment in 1987. Standard error of the means are shown as vertical lines only for treatments T1 and T6

Table 6. Mean almond nut retention for three levels of irrigation in 1985, 1986, 1987 as a function of flower counts and early nut set at the West Side Field Station near Five Points, CA

Year	Day of year	Nut retention as percent of initial flower count[a] (%)			Nut retention as percent of initial nut count[b] (%)		
		Treatment			Treatment		
		T1	T3	T5	T1	T3	T5
1985	178	24	32	35	56	62	64
		(2)[c]	(3)	(3)	(3)	(3)	(4)
	241	20	28	30	46	55	55
		(2)	(3)	(3)	(3)	(3)	(5)
1986	162	30	ND[d]	26	75	75	73
		(4)	–	(3)	(5)	(3)	(4)
	232	28	23	26	71	72	74
		(3)	(2)	(3)	(4)	(3)	(4)
1987	160	20	23	27	67	73	75
		(4)	(2)	(3)	(7)	(4)	(5)
	237	19	22	26	63	70	73
		(3)	(2)	(1)	(5)	(3)	(2)

[a] Mean of flower counts made on calendar days 58 to 68 in 1985, 55 to 70 in 1986, and 61 to 73 in 1987. Mean of counts on two marked branches on each of 3 trees per treatment in blocks 3, 4, and 5; $n = 18$ branches

[b] Mean of nut counts on two marked branches on each of 3 trees per treatment plot in blocks 3, 4, and 5 ($n = 18$ branches) measured initially on day of year 112, 91, and 105 in 1985, 1986, and 1987, respectively

[c] Values shown in parentheses below mean values are standard error of the mean

[d] ND = no data

two years, perhaps reflecting higher winter rainfall in early 1986. Lower prevailing afternoon vapor pressure deficits during most July and August measurement dates in 1986 may have also contributed to lower leaf water potentials than in similar periods in 1985 and 1987. Mid-season LWP vaues of high water application treatments in this study were 0.1 to 0.3 MPa lower than reported for well-watered almonds in several trickle irrigation studies under conditions of coarser soils and lower ET_0 (Ruiz-Sanchez et al. 1988; Castel and Fereres 1982).

The slowly-developing water deficits produced with continuous deficit irrigation in the low water treatments of this study are in contrast to the long-term (one to two month duration) periods without irrigation investigated in studies by Uriu et al. (1970), El-Sharkawi and El-Monayeri (1976), Castel and Fereres (1982), and Krauter (1985). Plant responses to even the most severe continuous deficit irrigation treatments in this study were principally reduced overall plant size and growth, with little leaf shedding or changes in leaf orientation during the irrigation season, and maintenance of at least partially open stomata in all treatments (Fig. 4). Leaf conductance to water vapor (g_c) of treatments T1 and T2 were significantly lower than other treatments on most measurement dates. Leaf conductance declined linearly with decreasing LWP, similar to Torrecillas et al. (1988), although no consistent threshold LWP associated with reduced g_c could be identified. During the month of July in all three years, the minimum g_c measured in illuminated spur branch leaves in treatment T1 and T6 averaged 0.22 and 0.62 mol m^{-2} s^{-1}, respectively.

Tree growth and nut yields are a composite response to plant water status over a long period, and while several water-deficit sensitive growth stages exist for almond (Micke and Kester 1978), a critical LWP or g_c value below which yield or long-term growth will be affected has not been identified (Castel and Fereres 1982; Ruiz-Sanchez et al. 1988). In this study, however, maintenance of LWP higher than −2.3 MPa during early nut development (March through May) and greater than −2.5 MPa the remainder of the irrigation season was correlated with sustained higher vegetative growth rates and nut yields. Correlations between LWP and yield or trunk cross-section areas within any year were positive and significant, with all r^2 values in excess of 0.9.

Almond nut retention

In 1985 and 1987, nut retention increased with increases in applied water, although no significant differences occurred across treatments in 1986. Additional nut loss during the period from June through a time just before harvest in any year ranged from near zero to 18% (Table 6).

Nut retention was also evaluated with respect to the initial nut counts taken in April of each year to determine nut loss during the summer. In 1985 and 1987, the 50% ET_c irrigation treatment (Table 6) and 75% ET_c treatment (data not shown) had significantly higher nut losses than the other treatments, while no significant differences occurred in 1986. Trickle irrigation at levels above 100% ET_c reduced nut loss by only 2% to 4% over the three-year study.

Nut meat yield and kernel weight

In 1985 and 1987, nut meat yields increased significantly with increases in applied water from 50% ET_c through 125% ET_c (Table 7). Results were mixed in 1986, with

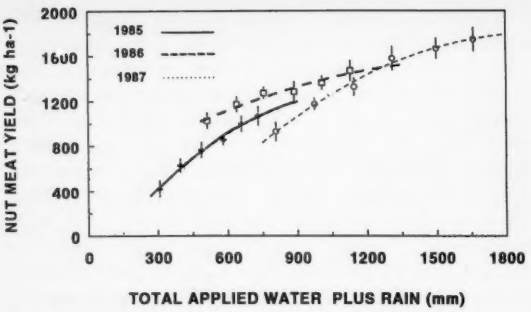

Fig. 5. Almond nut meat yields as a function of total applied water plus rain in 1985, 1986, 1987. Second-degree polynomial equations fitted to data for individual years were as follows: (1985) $y=51.22+2.45\,x-0.0013\,x^2$, $r^2=0.993$; (1986) $y=793.4+1.04\,x-0.0003\,x^2$, $r^2=0.958$; (1987) $y=277.4+1.99\,x-0.0007\,x^2$, $r^2=0.993$. Standard error of the means are shown as vertical lines for each data point

Table 7. Mean almond (Ruby variety) nut meat yield and kernel weight as a function of trickle irrigation rate. Orthogonal comparisons within each year are shown for major treatment comparisons

Irrigation treatment code	Mean nut meat yield (kg ha^{-1})[a]					Mean kernel weight (mg kernel^{-1})[b]		
	Year					Year		
	1983	1984	1985	1986	1987	1985	1986	1987
T1	340	565	420	1025	926	594	862	787
T2	374	716	627	1171	1173	677	901	881
T3	392	759	762	1273	1327	742	901	918
T4	388	950	853	1284	1577	781	892	953
T5	472	883	996	1362	1666	828	940	946
T6	405	848	1068	1467	1746	864	946	974
Comparisons[c]								
T1 vs. T2	NS	**	**	**	**	*	**	**
T1 vs. T3	NS	**	**	**	**	**	**	**
T2 vs. T3	NS	NS	**	NS	*	*	NS	*
T2 vs. T4	NS	**	**	NS	**	**	NS	**
T3 vs. T4	NS	*	*	NS	**	NS	NS	NS
T3 vs. T5	*	NS	**	*	**	**	NS	NS
T3 vs. T6	NS	NS	**	**	**	**	NS	NS
T4 vs. T5	*	NS	*	NS	NS	NS	NS	NS
T4 vs. T6	NS	NS	*	*	*	*	NS	NS
T5 vs. T6	*	*	NS	NS	NS	NS	NS	NS

[a] Based on the mean nut yield of 5 trees harvested in each of 7 blocks per treatment. Planting density equivalent to 268 trees per ha

[b] Based on the average kernel weight of 100 kernels from a 4 to 7 kg subsample of harvested nuts from 5 trees per treatment in each of 7 blocks per treatment

[c] Orthogonal comparisons within a year designated as NS, *, or ** were not significant, significant at the $P<0.10$ level, or significant at the $P<0.05$ level, respectively

higher yields in 150% and 175% ET_c treatments (T5, T6) than at lower ET_c levels. The second degree polynomial prediction equations for nut yield as a function of total applied water plus rain during each year are presented in Fig. 5. Although the polynomial curve fits (Fig. 5) seem to indicate that nut yields continue to increase with water applications greater than 150% ET_c, there were no consistent, significant increases in indices of tree growth or nut yields at water applications in excess of 150% ET_c (Tables 3, 7).

In terms of water use, mature almond trees were defined by Micke and Kester (1978) as those shading more than 70% of the ground area, and they reported an average annual ET_c in the San Joaquin Valley as 40.6 m^3 tree^{-1}. Water applications to treatment T3 trees with a shaded ground area of 30 to 32% in this study were 65 to 70% of estimated ET_c for a mature orchard, as described using the crop coefficient procedures of Fereres et al. (1981). Even though they did not approach the 70% ground area shading of a mature orchard, trees irrigated at the 150% and 175% ET_c levels received applied water equal to or in excess of mature almond ET_c (Micke and Kester 1978).

Tree growth, nut yields and plant water status measurements all indicate that the 100% ET_c treatment was deficit-irrigated, with reductions in yield and growth relative to the 150% and 175% ET_c treatments. These findings appear contradictory to previously reported work of Nightingale et al. (1991) from this same study showing that the leaching fraction in the upper 1 m of the soil beneath the trickle lateral out to about 1 m from the lateral was 10 to 22% of applied water. The existence of significant leaching in the 100% ET_c treatment, where plant water deficits resulted in reduced tree growth and yields, is somewhat difficult to reconcile. It is possible that irrigations were not correctly scheduled to meet plant water needs over time, resulting in over-irrigation and leaching during some periods and under-irrigation during critical periods where water deficits influenced growth and yield. LWP data does not support this conclusion, however, since treatments T1 through T3 had consistently lower LWP than higher water application treatments during all measured periods from May through August (Table 5). Another possibility is that significant leaching losses in some areas of the wetted soil volume resulted from the mismatch of the small infiltration area of the single trickle line and the relatively high trickle application rates in this study, as suggested by Nightingale et al. (1991). This second possibility is more compatible with the coexistence of plant water deficits in treatments T1 through T4 and significant leaching losses identified by Nightingale et al. (1991). In future studies it may be worthwhile to determine if changes in irrigation frequency, application rates, or addition of more laterals to wet a larger soil volume can more evenly distribute water applications over time and space and avoid some of the leaching losses suggested in this study.

Nightingale et al. (1991) previously described the influence of long-term use of this quality of water on soil accumulations of boron and other irrigation water constituents. Problems of accumulation of salt and boron at the perimeter of the wetted soil volume were identified, particularly in the low water application treatments. The irrigation water in this study was not found to cause a serious salinity or boron hazard in the short-term (several years) (Nightingale et al. 1991). However, if minimal leaching fractions (less than 0.05 to 0.10) were achieved, salt and boron could accumulate within the root zone in

Table 8. Water use efficiency (determined as kg of kernels per m^3 of applied water) in trickle irrigated almonds at the West Side Field Station in 1985 through 1987. Orthogonal comparisons are shown for major treatment comparisons

Irrigation treatment code	Water use efficiency ($kg\ m^{-3}$)[a]		
	Year		
	1985	1986	1987
T1	0.257	0.385	0.246
T2	0.249	0.302	0.213
T3	0.225	0.249	0.183
T4	0.198	0.199	0.175
T5	0.193	0.179	0.153
T6	0.182	0.166	0.141
Comparisons[b]			
T1 vs. T2	NS	**	*
T1 vs. T3	NS	**	**
T2 vs. T3	NS	NS	*
T2 vs. T4	**	**	**
T3 vs. T4	*	*	NS
T3 vs. T5	**	**	*
T3 vs. T6	**	**	**
T4 vs. T5	NS	NS	NS
T4 vs. T6	NS	**	**
T5 vs. T6	NS	NS	NS

[a] Mean of 35 trees

[b] Orthogonal comparisons within a year designated as NS, *, or ** were not significant, significant at the $P<0.10$ level, or significant at the $P<0.05$ level, respectively

detrimental amounts over a period of several years. The threshold salinity for growth reductions in almond is 1.5 dS m^{-1} (Maas 1986). Accumulations of boron and salinity within the root zone in the low applied water treatments (T1, T2) could eventually interact with the effects of deficit irrigation in reducing nut yields and size. Hoffman et al. (1989) observed both short-term and long-term growth and yield reductions in plums, another *Prunus* spp. (*Prunus salicina*), at average root zone salinities lower than those observed in this study.

The mean almond kernel weights as a function of year and irrigation treatment are shown in Table 7. Kester et al. (1985) stated that the Ruby cultivar produces medium-sized kernels, 945 to 1135 mg $kernel^{-1}$. During 1985, each incremental (25% of ET_c) increase in applied water resulted in a significant increase in kernel weight. Since all 1985 kernel weights were lower than the characteristic values stated by Kester et al. (1985), the combination of a mid-summer 20-day period with peak daily temperatures 3 to 5°C above normal and more severe water deficits in early summer (Table 5) may have reduced kernel weights in all treatments. In 1986 and 1987, kernel weights were significantly smaller only in the low ET_c treatments (T1 in 1986, T1 and T2 in 1987). While a variety of factors could be involved in the response of kernel weights to applied water, even moderate water stress during the embryo growth phase has been associated with reductions in the expansive growth of almond kernels (Micke and Kester 1978).

Water use efficiencies (WUE), kg nut meat per m^3 of trickle applied water, were calculated for each of the 3 years (Table 8). For the 3-year means, WUE ranged from a high of 0.296 for the lowest water application treatment (T1) to a low of 0.163 for the highest irrigation level (T6), with significantly higher WUE in the lower three water application treatments (T1, T2, T3) than in higher applied water treatments in at least two out of three years.

Conclusions

During the 1985 through 1987 period of this study, leaf conductance, leaf water potential, and soil water content data indicated relatively consistent differences in soil and plant water status across irrigation treatments. Deficit irrigation resulted in significantly smaller trees and reduced production of leaves and fruiting sites. Tree growth, nut yield, and plant water status indicators improved significantly with increases in applied water up to the T4 (125% ET_c) level, and did not generally increase significantly at the 150% and 175% ET_c levels.

Differential treatments prior to 1984 resulted in significantly smaller trees (trunk diameter, canopy size) in the 50% ET_c treatment at the initiation of the new experiment when compared to other treatments. These carryover effects of the prior experiment prevented identification of the absolute responses to the 1984 through 1987 50% ET_c treatment. The initial trunk cross-section area of T4 was also significantly greater than treatment T2. No other treatments were significantly different in measured growth parameters at the time of initiation of the new experiment.

Annual tree growth and nut meat yield were positively correlated ($r^2>0.9$) with averages of afternoon LWP measured during May through August. Sustained LWP of higher than −2.3 MPa during early nut development (March through May) and higher than −2.5 MPa the rest of the irrigation season were correlated with the highest growth rates and nut meat yields.

Water applied in the 100% ET_c treatment, determined as described by Fereres (1981) with additional adjustments according to soil water depletion data, was not adequate to maximize yields and maintain non-water-stressed trees under the conditions of this trickle irrigation experiment. The water application amounts in the 125% or 150% ET_c treatments may more closely represent irrigation needed to maximize growth and yield under conditions (climate, soil, irrigation system management) at the experiment site. Rolston et al. (1991) and Nightingale et al. (1991) previously defined the uncertainty involved in quantifying actual ET_c and deep percolation for this experiment. If the irrigation system and management could be improved to better store applied water within the active root zone, the high leaching losses described by Nightingale et al. (1991) would be avoided. With such improvements, yield and growth might be maximized at lower irrigation amounts (closer to 125% of ET_c calculated by methods of Fereres (1981)).

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Effect of salinity and K/Na ratio of irrigation water on growth and solute content of *Atriplex amnicola* and *Sorghum bicolor*

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Abstract. Total salinity and K/Na ratios in the irrigation water were varied for two different types of plants; sorghum, a moderately salt tolerant crop plant whose growth is inhibited by high NaCl levels, and *Atriplex*, an extreme halophyte whose growth is stimulated by high NaCl levels. Sorghum growth was significantly reduced at all salinity levels from 50 to 150 mM, but *Atriplex* growth was not reduced until salinity exceeded 100 mM. In both species, growth reductions were increased by increasing the ratio of K to Na from 1/100 to 1/1 in the irrigation water. The amount of K and Na accumulated in the leaves of *Atriplex* reflected the relative amounts in the irrigation water, but in sorghum most of the increase in the concentration of K + Na was due to the increase in K regardless of the ratio of K/Na in the irrigation water. Nitrate levels in leaves of sorghum were little affected by salinity but were decreased in *Atriplex* by the combination of high salinity and K/Na ratio. The lower amount of salt accumulation in sorghum was compensated for by greater accumulation of soluble organic compounds, such as proline and soluble carbohydrates, that presumably were osmotically active and could contribute to osmotic adjustment. All of the results supported the general conclusion that, despite differences between glycophytes, such as sorghum, and halophytes, such as *Atriplex*, in sensitivity to the total soluble salt concentration in irrigation water, in both species growth was reduced more by K/Na ratios of 1/1 and 1/10 than by a ratio of 1/100 at those salinity levels that significantly reduced growth in each species.

The solutes responsible for increasing salinity in a plant's environment usually are Na salts. Plants growing in such environments are basically of two types, glycophytes and halophytes. Glycophytes are relative excluders of the Na, and growth is reduced by relatively low levels of Na in the leaves. In contrast, halophytes are relative accumulators of Na, and many of them show enhanced growth at relatively high levels of Na in the leaves. In halophytes, Na is the major solute contributing to decrease in leaf osmotic potential in response to increased salinity in the root environment. Since glycophytes exclude most of the Na, K is the primary inorganic solute that is accumulated in leaves in response to increased external salinity. However, in spite of the similarity between Na and K, they do not elicit the same responses in plants (Hylton et al. 1967; Aslam 1975; Helal et al. 1975; Eshel 1985; Matoh et al. 1986). Potassium is the only monovalent cation that is essential for growth of all higher plants. Sodium has only been shown to be essential for some species, but appears to stimulate the growth of others (Brownell 1967; Brownell and Crossland 1972; Rush and Epstein 1981; Eshel 1985). In some glycophytes, such as sorghum (Weimberg et al. 1984) and mung bean (Salim and Pitman 1983), high levels of K were found to be more harmful than high levels of Na, but in other cases addition of K salts to the nutrient medium reduced the harmful effects of high Na levels (Hylton et al. 1967; Helal et al. 1975). In halophytes, high K levels have been speculated to cause similar responses (Flowers et al. 1977; Flowers and Lauchli 1983). However, since the response of both a glycophyte and a halophyte to high K levels at different salinities has not been determined under similar conditions, it is not valid to conclude that high external levels of K have the same effect on both types of plants.

This study was designed to compare the effects of different salinity levels and K/Na ratios on growth and solute content of two different types of plants, a moderately salt tolerant crop plant (*Sorghum*), whose growth is inhibited by high NaCl levels, and an extreme halophyte (*Atriplex*), whose growth is stimulated by high NaCl levels. The hypothesis tested was that high levels of K in

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the root environment will not reduce growth in the halophyte as much as in the glycophyte, as long as Na is present in equal or greater amounts.

Materials and methods

Experimental procedure

Seeds of *Sorghum bicolor* L. "BTX 62" were sown in 10 liter plastic pots containing 12 kg air-dried and sieved sand and irrigated with a modified Hoagland solution (see below). Rooted stem cuttings of *Atriplex amnicola* were transplanted directly into such pots, one per container, and irrigated with the same solution. After 15 days, the sorghum seedlings were thinned to 5 plants per pot, and the treatments began.

Plants were grown in an evaporately-cooled greenhouse in Tucson, Arizona under high natural radiation levels (ca. 800–1050 $W m^{-2}$), high temperatures (ca. 20–24 °C nights/26–30 °C days) and moderate humidity levels (70–80% RH). See Glenn (1984) for details of seasonal environmental conditions in a similar greenhouse at the same location. The modified K-free Hoaglands solution was prepared by replacing KH_2PO_4 with NaH_2PO_4 and KNO_3 with additional $Ca(NO_3)_2$. The Ca and NO_3 concentrations were 5 mM and the PO_4 concentration was 2 mM. Known amounts of KCl and NaCl were added to give final concentrations of (K + Na) of 4 (control), 100, 200, and 400 mmol for *Atriplex* and 4 (control), 50, 100, and 150 mmol for sorghum. At each level of salinity there were three different K/Na ratios of 1/1, 1/10, and 1/100, so the total number of treatments was 12 for each species. The treatments were laid out in a randomized block design with 4 replicates.

Pots were weighed every other day to determine the amount of evapotranspiration. The pots were watered with sufficient amounts of the treatment solutions to restore the soil to field capacity plus an additional amount equivalent to twice the amount of evapotranspiration to insure adequate leaching. Drainwater from each pot was quantitatively collected and the electrical conductivity measured to insure that the desired salinity levels in each pot were maintained.

Plant harvest

Plant shoots were harvested 50 days after the initiation of the treatments. Fresh and dry weights were determined, and subsamples (1 g) of fresh leaves were frozen and later used for organic analyses. After harvesting, the experiment was repeated for *Atriplex* with the same treatments and experimental measurements.

Inorganic analysis

The oven-dried material was dry ashed at 550 °C for 5 h, the ash was dissolved in dilute HCl (Chapman and Pratt 1961), and Na, K, Ca, Mg were assayed by atomic absorption spectroscopy. Oven-dried material was ground and extracted for 0.5 h with hot distilled water, and nitrate was determined colorimetrically with a Technicon autoanalyzer.

Organic analysis

Thawed fresh material was extracted with methanol:chloroform:water, 12:5:1 (v:v:v) (Singh et al. 1973). Proline was determined with the acid ninhydrin method of Troll and Lindsley (1955), except that toluene was used instead of benzene. Free amino acids were determined with ninhydrin reagent (Rosen 1957). Glycine was used as the standard, so the results are presented as glycine equivalents.

Total soluble carbohydrate was determined with a mixture of phenol and H_2SO_4 (Dubois et al. 1956). Since glucose was used as the standard, the results are presented as glucose equivalents.

Water potential

Water potentials of leaf discs were determined psychrometrically with a Wescor Model HR33T microvoltmeter.

Results

Fresh and dry weights

The effects of salinity and K/Na ratios on shoot fresh and dry weights of *Atriplex* were significant at the 5% level, but the interactions were not (Table 1). Regardless of the K/Na ratio, the 100 mmol treatment did not significantly affect fresh weight in experiment I, but it did have a significant effect in experiment II. However, further increases in salinity reduced fresh weight significantly in both experiments. At all salinity levels, decreasing the K/Na ratio increased the fresh weight in both experiments.

Similar to fresh weight, the dry weights were not significantly reduced by the 100 mmol treatment (regardless of K/Na ratio), but further increases in salinity significantly reduced dry weight. Decreasing the K/Na ratio from 1/1 to 1/100 within each salinity level significantly increased dry weight in both experiments.

Fresh and dry weights of sorghum decreased significantly with all increases in salinity level, regardless of K/Na ratio (Table 2). There was a significant interaction between salinity level and K/Na ratio in sorghum. Consequently, decreasing the K/Na ratio did not have as clear

Table 1. Effect of salinity and K/Na ratio on shoot fresh and dry weights of *Atriplex amnicola*

Salinity treatment	K/Na	Fresh weight		Dry weight	
		I*	II**	I	II
(K + Na) mmol/l		g/plant			
4 (control)	1/1	240	231	63	53
	1/10	270	268	70	59
	1/100	278	276	72	61
100	1/1	242	220	67	55
	1/10	263	234	71	58
	1/100	266	240	72	58
200	1/1	161	161	51	50
	1/10	176	174	53	57
	1/100	197	192	57	58
400	1/1	75	65	29	24
	1/10	93	80	35	28
	1/100	116	93	42	32
L.S.D. (0.05)					
For salinity (S)		27	22	7	6
For K/Na ratios (R)		24	19	6	5

* Experiment I
** Experiment II

Table 2. Effect of salinity and K/Na ratio on fresh and dry weights of *Sorghum bicolor*

Salinity treatment	K/Na	Fresh weight	Dry weight
(K + Na) mmol/l		g/plant	
4 (control)	1/1	96.0	18.4
	1/10	93.0	18.1
	1/100	104.1	19.7
50	1/1	74.9	14.9
	1/10	66.5	13.0
	1/100	64.8	14.6
100	1/1	42.8	8.6
	1/10	48.7	9.8
	1/100	52.9	10.3
150	1/1	21.9	4.4
	1/10	27.6	5.5
	1/100	33.2	6.6
L.S.D. (0.05)			
For salinity (S)		1.8	0.7
For K/Na ratios (R)		2.6	0.6
For S × R		3.2	1.2

Table 3. Effect of salinity and K/Na ratio on leaf water potential of *Atriplex* and *Sorghum*

Treatments	K/Na	Water potential (MPa)		
		Atriplex		*Sorghum*
Salinity [mM (K + Na)]		Experiment I	Experiment II	
4 (control)	1/1	−1.4	−1.4	−1.0
	1/10	−1.3	−1.2	−1.1
	1/100	−1.3	−1.5	−1.1
50	1/1			−1.0
	1/10			−1.2
	1/100			−1.2
100	1/1	−2.0	−2.1	−1.2
	1/10	−1.8	−1.7	−1.4
	1/100	−1.9	−2.1	−1.4
150	1/1			−1.5
	1/10			−1.4
	1/100			−1.7
200	1/1	−3.1	−2.9	
	1/10	−3.0	−3.3	
	1/100	−3.0	−2.8	
400	1/1	−4.3	−4.3	
	1/10	−4.1	−4.5	
	1/100	−4.2	−4.2	
L.S.D. (0.05)				
For salinity (S)		0.2	0.2	0.1
For K/Na ratio (R)		–	–	–
For S × R		–	0.3	–

an effect with sorghum as with *Atriplex*, except at the two highest salinity levels where decreases in the ratio significantly increased both fresh and dry weights.

Leaf water potential

In both species, the leaf water potential decreased with increased salinity (Table 3). The decline was greater in *Atriplex* than in sorghum, both in absolute value and percent decrease. For example, at the 100 mM level, the absolute value was over 50% lower than at the control level in *Atriplex* while in sorghum the difference was less than 40%. Water potential was not significantly affected by the K/Na ratio, but rather seemed to respond to total salinity.

Ash content

At all salinity levels, including the relatively non-saline control level, the ash content of *Atriplex* was considerably higher than that of sorghum (Tables 4 and 5). In both species, the ash content increased significantly with increases in salinity level of the irrigation water. The K/Na ratio of the water did not significantly affect the ash content of *Atriplex*, at any salinity level, but in sorghum, at the higher salinity levels (100 and 150 mM), ash content was significantly decreased as the ratio of K to Na in the irrigation water declined.

Cation and nitrate concentration

Cation and nitrate concentrations in the leaf tissue of *Atriplex* are from Experiment I only (Table 4). The data from Experiment II were very similar. As expected from the ash contents, the concentrations of Na and K in the leaf tissues increased with salinity in both *Atriplex* (Table 4) and sorghum (Table 5). In *Atriplex*, Na and K increased in relation to the increases in salinity when they were present in equal concentrations in the irrigation water, but when the ratio of K to Na was less than 1, most of the increase in salt content was accounted for by Na. This is indicated by the K/Na ratios in the tissue (Table 4). The K concentration changed very little with increases in salinity beyond the 100 mM level at K/Na ratios of 1/10 and 1/100.

In *Sorghum*, in contrast, most of the salinity increase in the plant tissue was accounted for by K. Sodium did not increase much until the external salinity exceeded 100 mM (Table 5). In fact, both Na and K increased dramatically at the 150 mM level. Even when the K/Na ratio in the irrigation water heavily favored Na, the plants still accumulated large quantities of K. As a result, the K/Na ratio in the tissue remained high, even at external ratios of 1/100. If the dramatic increase in tissue salt concentration had been the result of a complete loss of the ability of the root membranes to control salt uptake, the ratio of K/Na in the tissue might be expected to more closely reflect the ratio of those ions in the external solution. Since that was not the case, the membranes apparently still retained some differential permeability, even at the external salt concentration of 150 mM.

Table 4. Effect of salinity and K/Na ratio on ash and mineral content of *Atriplex amnicola*

Salinity treatment	K/Na	Ash %DW	Na	K	Ca	Mg	K/Na	NO_3 mg/g DW
			meq/100 g DW					
(K + Na) mmol/l								
4 (control)	1/1	21.1	94	75	92.8	70.0	0.8	7.3
	1/10	21.3	187	48	88.6	67.8	0.3	8.3
	1/100	21.9	214	49	96.0	75.3	0.2	7.6
100	1/1	28.5	203	197	84.8	60.8	1.0	7.1
	1/10	28.0	367	138	85.5	66.3	0.4	7.7
	1/100	27.1	425	86	84.8	63.0	0.2	8.2
200	1/1	31.2	229	228	84.0	40.5	1.0	4.9
	1/10	29.4	402	129	96.0	67.3	0.3	6.8
	1/100	29.9	465	118	99.0	64.0	0.3	7.4
400	1/1	32.3	241	256	79.0	32.3	1.2	2.9
	1/10	29.9	432	126	89.8	47.3	0.3	5.5
	1/100	31.0	542	92	85.1	48.5	0.2	6.7
L.S.D. (0.05)								
For salinity (S)		0.9	55	10	–	7.5	–	0.9
For K/Na ratios (R)		–	48	8	–	6.5	–	0.8
For S × R		–	–	17	–	–	0.2	–

Table 5. Effect of salinity and K/Na ratio on ash and mineral content of *Sorghum bicolor*

Salinity treatment	K/Na	Ash %DV	Na	K	Ca	Mg	K/Na	NO_3 mg/g DW
			meq/100 g DW					
(K + Na) mmol/l								
4 (control)	1/1	7.3	1.3	50.8	28.6	38.4	40.9	1.2
	1/10	6.4	1.3	37.2	29.8	39.5	29.3	1.0
	1/100	6.9	1.4	43.3	32.4	40.2	31.3	0.6
50	1/1	8.6	1.3	75.2	31.4	41.6	60.7	0.9
	1/10	8.0	1.7	63.7	32.2	36.5	41.7	0.8
	1/100	8.1	1.4	61.0	33.2	39.6	43.2	1.9
100	1/1	11.6	3.5	128.7	31.5	37.6	47.9	1.5
	1/10	9.6	4.9	70.7	29.6	36.2	15.3	1.8
	1/100	10.0	7.0	63.8	32.8	38.4	9.4	1.9
150	1/1	23.9	42.9	323.3	31.7	39.3	15.5	2.0
	1/10	15.9	52.9	160.5	32.8	36.7	3.6	1.8
	1/100	13.0	55.2	143.5	28.0	36.7	2.7	1.7
L.S.D. (0.05)								
For salinity (S)		1.1	13.0	15.5	–	–	8.2	–
For K/Na ratios (R)		0.9	–	13.5	–	–	7.1	–
For S × R		1.8	–	26.9	3.6	1.7	–	–

The divalent cation content of the tissue did not change much with increases in external salinity. In both species, the changes in Ca concentration were not significant (Tables 4 and 5). The changes in Mg concentration were not significant in sorghum, but in *Atriplex* the Mg concentration did decline with salinity. At the higher salinities there also was a significant effect of K/Na ratio in the irrigation water. When K represented half of the salinity, the Mg concentration was significantly lower than when K was only 1/10 or 1/100 of the total salinity.

The nitrate concentration of the *Atriplex* tissue declined with increasing salinity (Table 4), and within all salinity levels the nitrate concentration was significantly less at the higher K/Na ratios. In sorghum, however, the nitrate concentration of the tissue did not change significantly with either salinity or K/Na ratio (Table 5).

Soluble carbohydrate

Soluble carbohydrate content of plant tissue increased much more in sorghum (Table 7) than in *Atriplex* (Table 6) in response to salinity. The K/Na ratio of the irrigation water did not have much influence in *Atriplex*, the differ-

Table 6. Effect of salinity and K/Na ratio on soluble carbohydrates, free amino acids and proline contents in leaves of *Atriplex amnicola*

Salinity treatment	K/Na	Soluble carbohydrate		Free amino acids		Proline	
		Glucose equiv.		Glycine equiv.			
		I*	II*	I	II	I	II
(K + Na) mmol/l		µmol/g fresh weight					
4 (control)	1/1	2.2	1.8	6.5	5.8	0.3	0.3
	1/10	2.2	1.9	6.5	5.4	0.3	0.3
	1/100	2.6	1.7	7.4	6.8	0.5	0.4
100	1/1	2.5	2.4	6.5	6.1	0.8	0.7
	1/10	2.2	2.8	7.3	6.8	0.7	0.7
	1/100	2.6	3.0	6.7	6.7	0.9	0.9
200	1/1	2.7	3.2	7.1	7.1	1.2	1.2
	1/10	2.7	3.3	7.2	6.9	1.1	1.1
	1/100	2.8	3.3	7.3	7.8	1.2	1.2
400	1/1	2.9	3.5	6.9	7.3	8.0	5.8
	1/10	2.6	3.6	9.5	8.8	3.9	3.2
	1/100	2.6	3.8	8.7	9.2	2.9	2.4
L.S.D. (0.05)							
For salinity (S)		0.2	0.6	0.7	0.9	0.7	0.4
For K/Na ratios (R)		0.1	–	0.6	0.8	0.6	0.3
For S × R		0.3	–	1.3	–	1.2	0.6

* Experiment I
** Experiment II

Table 7. Effect of salinity and K/Na ratio on soluble carbohydrates, free amino acids and proline contents in leaves of *Sorghum bicolor*

Salinity treatment	K/Na	Soluble carbohydrate	Free amino acids	Proline
		Glucose equiv.	Glycine equiv.	
(K + Na) mmol/l		µmol/g fresh weight		
4 (control)	1/1	3.7	7.1	0.1
	1/10	3.8	6.4	0.1
	1/100	3.2	7.3	0.3
50	1/1	3.7	15.6	1.7
	1/10	5.5	12.4	1.0
	1/100	5.7	14.9	1.8
100	1/1	4.8	18.2	6.9
	1/10	6.1	18.3	5.1
	1/100	7.8	16.8	4.2
150	1/1	4.9	22.2	12.7
	1/10	6.5	20.4	6.3
	1/100	8.9	22.5	4.5
L.S.D. (0.05)				
For salinity (S)		0.3	0.8	0.7
For K/Na ratios (R)		0.3	0.7	0.6
For S × R		0.6	1.3	1.2

* Experiment I
** Experiment II

ences being non-significant in the second experiment and small, albeit significant, in the first experiment. On the other hand, soluble carbohydrate content of the tissue in sorghum increased considerably as the K/Na ratio of the irrigation water decreased at all salinity levels beyond the control level.

Amino acids

In general, the amino acid content of *Atriplex* tissue was not affected much by the external salinity level nor by the K/Na ratio of the irrigation water (Table 6). The proline level was increased slightly by the intermediate salinity levels, and it was considerably higher at the highest salinity level. At that high salinity level, the proline content was highest at the highest K/Na ratio, but at the other salinity levels the proline content was not affected.

In sorghum, the proline content steadily increased with salinity. At the two higher salinity levels, the proline content was significantly higher when the K/Na ratio was higher, similar to the situation in *Atriplex*.

Discussion

As is characteristic for the two types of plants represented, fresh and dry weights of the glycophyte, sorghum, decreased with each increment of added salinity, but were not affected in the extreme halophyte, *Atriplex*, until salinity exceeded 100 mM. For some reason or other, however, the *Atriplex* did not have significantly higher growth at 100 mM salinity than at the relatively non-saline level of 4 mM, a response that is not in agreement with the results of Aslam et al. (1986) for this same species. In both species, the growth reduction due to salinity was increased by increasing the K/Na ratio of the irrigation water, consistent with results obtained by others for these and similar species (Flowers et al. 1977; Weimberg et al. 1984). This response probably was due not only to the growth inhibiting effects of high levels of K (Munns et al. 1983; Salim and Pitman 1983; Weimberg et al. 1984) but also to the growth stimulating effects of Na, in halophytes (Brownell and Crossland 1972; Flowers et al. 1977; Eshel 1985) as well as glycophytes (Williams 1960; Brownell 1967; Devitt et al. 1984; Rathert 1983).

There were no apparent signs that either of the species suffered from water stress under any of the treatments. Leaf water potentials declined about as expected with increases in salinity in both species. The only salinity level that was common to both species was 100 mM, and that caused a drop in water potential in sorghum of 0.2 to 0.3 MPa and in *Atriplex* of 0.5 to 0.7 MPa. The 100 mM increase in K + Na of the irrigation water is equivalent to a drop in osmotic potential of about 0.45 MPa, so in one species the leaf water potential decrease was slightly less than the drop in external water potential and in the other slightly greater. *Atriplex* had a leaf water potential that was 0.2 to 0.4 MPa lower than that of sorghum even in the non-saline treatment. At 100 mM, the difference between the two species was 0.4 to 0.8 MPa. That may

be a reflection that sorghum is a relative excluder, and *Atriplex* a relative accumulator, of Na and Cl when present in high concentration in the root environment. This response apparently was a response to total salinity, since there were no significant differences in leaf water potential at different K/Na ratios at any salinity.

The relative difference in exclusion *vs* accumulation, alluded to above, is readily apparent when the tissue ion contents are considered. In *Atriplex*, the ash content of the leaves was high even under non-saline conditions (4 mM), and increased substantially with increasing salinity (Table 4). In contrast, the ash content of the leaves of sorghum was relatively low at the lowest salinity (4 mM), and it increased very little as salinity increased to 50 and 100 mM. At 150 mM external salinity, the tissue ash content increased dramatically, especially when K made up half of the salinity (Table 5). That clearly reflects the marked uptake of K in those plants. In *Atriplex*, both Na and K contributed equally to the increase in Na + K content of leaves when they were present in equal amounts in the irrigation water, and as the proportion of K in the irrigation water decreased, the relative contribution of K to leaf Na + K content decreased. In contrast, in sorghum most of the Na + K content was accounted for by increase in K regardless of the K/Na ratio in the irrigation water. This has been reported to be the case in numerous Graminaceous halophytes (Albert and Popp 1977; Gorham et al. 1980), and these results for sorghum indicate that it also could be true for Graminaceous glycophytes.

The total amount of K + Na accumulated in leaves was affected differently in the two species by the ratio of those two ions in the irrigation water. In *Atriplex*, the amount of K + Na in the leaves increased with decreasing proportion of K in the irrigation water, but in sorghum, the amount of K + Na tended to decrease with decreasing proportion of K in the irrigation water (Tables 4 and 5). Lauter et al. (1988) found increasing levels of K + Na in leaves of cotton as the proportion of K decreased in solutions with varying proportions of K and Na, which is similar to the results with *Atriplex* in this study. This may be related to cotton's higher tolerance of salinity than most crops.

Even though nitrate has been reported to play a role in osmoregulation in other species (Smirnoff and Stewart 1985; Veen and Kleinendorst 1985; Gorham et al. 1986), it did not seem to be involved in the species studied here. It either did not change significantly with salinity, as in sorghum (Table 5), or it decreased with salinity, as in *Atriplex* (Table 4). Such a decrease has been observed in other species as well (Abdel-Kadir and Paulsen 1982; Aslam et al. 1984). It is interesting to note that the salinity-induced decrease in nitrate content was enhanced by increasing the proportion of K in the irrigation water, the significance of which is not immediately obvious.

The lower amount of salt accumulation in sorghum in response to salinity was compensated for by greater accumulation of soluble organic compounds, which presumably were osmotically active and could contribute to osmotic adjustment. The increase in amino acids, and specifically proline, was much greater than the increase in soluble carbohydrates (Table 7). In *Atriplex*, the situation was similar, except that the increase in amino acids, including proline, was not nearly as great as in sorghum (Table 6).

In summary, the hypothesis posed at the outset of this study was not supported by the data. In spite of the ability of the halophyte, *Atriplex*, to accumulate and tolerate high levels of Na, K uptake still was high enough to cause significant growth reduction even when provided with equal concentrations of Na and K in the environment. For example, in sorghum at a K/Na ratio of 1/100, the DW at the highest salinity (150 mM) was 33% of that at the non-saline control, but when the K/Na ratio was 1/1, the DW at the highest salinity was only 24% of that at the non-saline control. In *Atriplex*, when the K/Na ratio was 1/100, the DW at the highest salinity (400 mM) was 52% in Experiment I and 60% in Experiment II of that at the non-saline control. However, when the K/Na ratio was 1/1, the DW at the highest salinity was only 45% and 46% of that at the non-saline control. Thus, even though the absolute amount of growth reduction due to the total salinity and to the relative amounts of Na and K present in the external solution was not the same in the two types of plants, it is apparent that they respond similarly to those environmental stresses.

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Overestimation of soybean crop transpiration by sap flow measurements under field conditions in Central Portugal

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Abstract. Direct measurements of the xylem sap flow by the stem heat balance technique can be a valuable aid for determining the irrigation demand of field crops. In the present study, soybean (*Glycine max* (L.) Merr.) sap flow was evaluated under well-watered and water-stressed conditions using Dynamax SGA10 sap flow gauges. Solar radiation was measured continuously throughout the growing season. Soil water content was measured before and after each irrigation. There was a close relationship between solar radiation and xylem sap flow. The water flux in the soybean stems responded realistically to changes in the soil water content. However, the absolute values of sap flow were highly questionable. Calculating crop transpiration from sap flow measurements, the results were up to 4 times as high as calculated transpiration from soil moisture data and simulated transpiration using the locally calibrated soybean crop growth model SOYGRO. A sensitivity analysis of the stem heat balance technique gave no indications of technique or input errors. The gauge design was possibly not appropriate for the outdoor installation on soybeans.

The water flux in the stem of intact plants can be measured directly using the stem heat balance (SHB) technique according to Sakuratani (1981). Since the xylem sap flow is closely related to transpirational water losses (about 99% of plant water uptake is lost by transpiration), sap flow is assumed to equal transpiration. The relative accuracy of the SHB method compared with direct weighing of water losses is reported to be about ±10% (Sakuratani 1981, 1984, 1987; Baker and Van Bavel 1987; Steinberg et al. 1990). However, most of the studies using the SHB technique were conducted in controlled environments. The objective of this study was to determine soybean crop transpiration by sap flow measurements under well-watered and water-stressed conditions in the field and to compare the results with soil moisture measurements and simulated transpiration by the locally calibrated crop growth simulation model SOYGRO V5.42 (Jones et al. 1989).

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Materials and methods

The research was conducted in collaboration with the Technical University of Lisbon (Instituto Superior de Agronomia, Departamento de Engenharia Rural) at the irrigation station 'António Teixeira' in Monte da Barca near Coruche (38° 57′ N, 8° 32′ W).

One hectare of soybeans *Glycine max* (L.) Merr. cv. Kingsoy, were sown on May 17, day of year (DOY) 137, in 1991 on a sandy soil with a sand portion of 88.3% to a soil depth of 60 cm. Row spacing was 50 cm, plant spacing 6 cm, and plant density 32 m^{-2}. Water was supplied by sprinkler irrigation. There were two treatments, (1) well irrigated (Control) and (2) water-stressed after bloom (Stress). The Stress treatment covered 0.25 ha and was not irrigated for 13 days (DOY 208–220).

Water flux in the stem of intact soybean plants was measured directly using the stem heat balance (SHB) technique after Sakuratani (1981). With the SHB method, the thermal energy balance of a stem section which is continuously heated over a short vertical distance is determined. The distribution of radial and vertical heat is measured and the convective heat transport by the sap stream can be calculated. The energy balance of a heated stem segment is expressed as:

$$Q_h = Q_r + Q_v + Q_f + S. \quad (1)$$

Q_h – heat flux applied to the stem (W), Q_r – radial heat flux away from the stem (W), Q_v – vertical heat flux through the stem (W), Q_f – heat flux carried by the xylem sap (W), S – rate of heat storage (W).

Heat storage (S) in stems of herbaceous plants is negligible because of the small size of the heated stem segment and near steady state conditions in the system (Ham and Heilman 1990). At low flow rates, however, the heat storage term should be included in the calculations (Groot and King 1992).

The energy input, Q_h, follows Ohm's law

$$Q_h = U^2/R. \quad (2)$$

U – input voltage (V), R – heater resistance (Ω).

The vertical heat conduction, Q_v, can be up and down the stem:

$$Q_v = Q_u + Q_d. \quad (3)$$

Q_u, Q_d – axial heat conduction up and down the stem (W).

Fourier's law for a one-dimensional heat flow describes the axial heat conduction:

$$Q_u = K_s \cdot A \cdot dT_u/dx \quad (4)$$

$$Q_d = K_s \cdot A \cdot dT_d/dx \quad (5)$$

K_s – thermal conductivity of the stem tissue ($W\,m^{-1}\,K^{-1}$), A – cross sectional area of the stem (m^2), dT_u, dT_d – temperature above and below the heater (K), dx – spacing between thermocouple junctions (m).

The radial heat loss, Q_r, is computed by

$$Q_r = K_g \cdot E. \quad (6)$$

K_g – thermal conductance constant for a gauge installation ($W\,V^{-1}$), E – radial temperature gradient (V).

Solving equation (1) for Q_f, the sap flow rate can be calculated as described by Sakuratani (1981) and Baker and Van Bavel (1987):

$$F = (Q_h - Q_v - Q_r)/(C_p \cdot dT). \quad (7)$$

C_p – specific heat of water ($W\,s\,g^{-1}\,K^{-1}$), dT – temperature increase of the sap (K).

The sensor (sap flow gauge) consisted of a thin resistance heater completely surrounding the stem and two pairs of thermojunctions which measured the temperature of the stem surface above and below the heater (dT_u, dT_u in Eqs. (4) and (5)). An eight junction thermopile, wired across the cork backing of the heater, measured radial heat loss (E in Eq. (6)).

In this study, eight of the improved four-channel-gauges (Steinberg et al. 1990) with weather shield kits were used (model SGA10, Dynamax, Houston, USA). To prevent wetting and improve thermal contact with the stem, an electrical insulating compound (model G4, Dow corning, Midland, USA) – was applied to the gauges (Van Bavel and Van Bavel 1990). Four sap flow gauges were attached to soybean stems (9 mm diameter) in the Control plot and another four in the Stress treatment. The input voltage (4–5 V) to the resistance heater of the gauges was supplied by an adjustable voltage divider and a datalogger-multiplexer unit (model 21X/AM32, Campbell Scientific, Leicestershire, UK) continuously recorded the electrical signals. Solar radiation was also recorded by the datalogger using a pyranometer (model SKS 1110, Skye Instruments, Llandrindod Wells, UK) at a height of 2 m above the soil surface. Energy was supplied by a 12 V battery which was constantly recharged by a 35 W solar panel (model M65, Arco Solar, Chatsworth, USA). An execution interval of 30 s was chosen for all sensors and every 30 min the averaged values were stored.

Since maximum rooting depth of soybeans was found to be 60 cm, soil water content was measured at six depths (0–60 cm) in 10 cm increments using a neutron probe (Didcot Instrument, Abingdon, UK). In every treatment three access tubes were used and at each depth three replications were measured. The moisture content of the surface layer (0–10 cm) was determined gravimetrically and multiplied with the dry bulk density to get the volumetric water content. Measurements were made one day before and after each irrigation. During stress periods, soil water was determined every second day.

For comparing the sap flow results with simulated crop transpiration, the soybean model SOYGRO V5.42 (Jones et al. 1989) was used. The model was calibrated at the experimental site in 1990 and 1991 for the cultivar Kingsoy using local weather, soil profile and management data (Gerdes 1993). For that purpose, leaf area index (LAI), dry matter accumulation and root length density were measured during the growing seasons. In SOYGRO, soil water balance, root growth and root water uptake are calculated using the model developed by Ritchie (1985). Saturated upper limit, drained upper limit and lower limit of plant available water for each soil layer were derived from laboratory measured pF-curves. Actual plant transpiration in the SOYGRO model depends on the potential evapotranspiration (E_0), calculated after Priestley and Taylor (1972), and the LAI. For LAI ≤ 3.0, transpiration is E_0 multiplied by a LAI dependent factor and when LAI > 3.0, plant transpiration is assumed to equal E_0. The rate of root water absorption depends on plant available soil water, root length density and soil water conductivity coefficients as defined by the soil profile input data. When the total root water uptake is less than actual plant transpiration in the model, a water stress factor reduces plant growth (Ritchie 1985).

Results and discussion

Diurnal course of sap flow and solar radiation in the well irrigated treatment is shown in Fig. 1. The sap flow curves represent two soybean plants measured with different gauges. There was a close relationship between sap flow and solar radiation as would be expected since solar radiation influences stomatal aperture, air temperature and vapour pressure deficit. These weather and plant factors affect directly and indirectly the rate of transpiration. Measurable sap flow began at 6:30 h and ceased between 20:00 h and 21:00 h. In all replications, the maximum sap flow was recorded between 13:00 h and 15:00 h and ranged from 55 to 95 $g\,h^{-1}$. The total sap flow for DOY 206 (Fig. 1a) was 583.6 g (ml) and for DOY 210 (Fig. 1b) 512.3 g.

Daily accumulated sap flow per soybean plant in the well-watered and water-stressed treatments together with the corresponding solar radiation data are shown in Fig. 2. Though standard deviations of sap flow were considerable for some days, there were pronounced differences between the treatments. In the water-stressed plot, the sap flow rate declined after DOY 213, seven days after the last irrigation. The gradual reduction of sap flow in both treatments after DOY 226 was due to the advanced growth stage of soybeans (decreasing LAI).

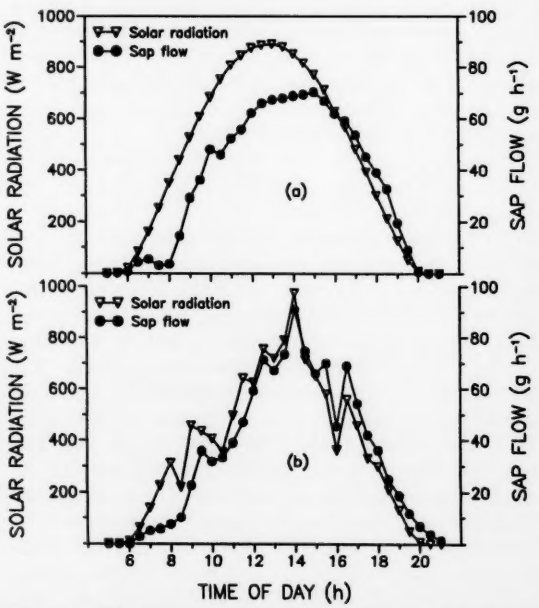

Fig. 1 a, b. Diurnal course of soybean sap flow and solar radiation on (**a**) DOY 206 and (**b**) DOY 210 in the well watered treatments

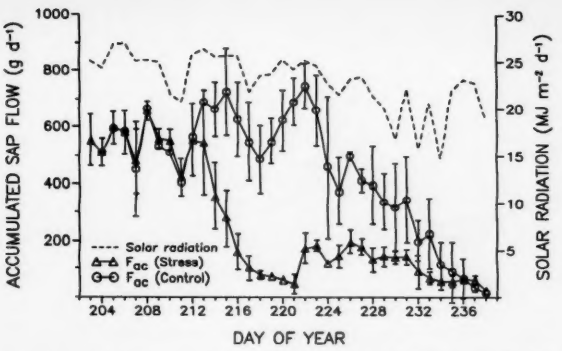

Fig. 2. Daily accumulated sap flow (F_{ac}) per soybean plant in the Control and Stress treatment (irrigated DOY 207 and 221, 1991) with corresponding solar radiation. The bars indicate standard deviations

There was a reasonable relationship between daily solar radiation and sap flow.

Soybean crop transpiration was calculated in this study by multiplying the daily accumulated sap flow per plant by a population of 32 plants m^{-2}. There were no major differences in leaf area and stem diameter among the soybean plants in the measurement area. The crop growth model SOYGRO was used to compute soybean transpiration based on weather conditions and simulated LAI. It is assumed that the Priestley-Taylor equation is appropriate to calculate E_0 for Central Portugal. The calibrated model satisfactorily predicted LAI, soil water content and water stress (Gerdes 1993). Therefore, the simulated SOYGRO results for crop transpiration are considered as reasonable reference values. However, a long-term validation of the calibrated model has not yet been carried out. In Table 1, the soybean crop transpiration derived from sap flow measurements is compared with the simulation results for crop transpiration obtained by the locally calibrated SOYGRO model. In the Control treatment, transpiration calculated using the SHB method on an average was 3.3 times as high as the simulated transpiration. In the Stress treatment, measured and simulated transpiration decreased uniformly. However, crop transpiration based on sap flow measurements was still about 4 times as high as the SOYGRO simulation results.

Water extraction according to soil moisture measurements (neutron probe) is shown in Table 2. The mean ET (evapotranspiration) values were calculated by determining the decrease of water content in the effective soil profile (0–60 cm depth) in the period between irrigations. Leaching of soil water was negligible and after DOY 200 (nine weeks after sowing), the soybean canopy totally covered the soil so that ET approximated actual plant transpiration. The mean ET values for both treatments were in good agreement with the simulated transpiration in Table 1. A transpiration rate of 4 to 8 mm d^{-1} at that growth stage (pod elongation) under non-water stress conditions appears reasonable (Doss and Thurlow 1974). The standard deviations for ET in Table 2 indicate that the transpiration rate measured by the Dynamax SGA10 sap flow gauges (Table 1) was unrealistic. Considering the standard deviations for the sap flow measurements (Fig. 2) for DOY 203 to 220, the transpiration in both treatments was still overrated.

Table 1. Soybean crop transpiration (T) measured using the stem heat balance (SHB) method and simulated using the crop growth model SOYGRO for the well irrigated (Control) and water-stressed (Stress) treatments in 1991

Day of year	Measured (SHB)		Simulated (SOYGRO)	
	Control T (mm d^{-1})	Stress[a] T (mm d^{-1})	Control T (mm d^{-1})	Stress[a] T (mm d^{-1})
203		17.7	5.4	5.4
204	16.4	16.3	5.3	5.3
205	19.0	19.1	5.7	5.7
206	18.7	18.6	5.9	5.9
207	14.4	15.3	5.9	5.9
208	21.3	21.0	5.9	5.9
209	17.1	17.9	5.3	5.3
210	16.4	17.7	4.5	4.5
211	13.0	13.6	4.2	4.2
212	18.1	17.8	5.4	5.4
213	22.1	17.5	6.0	4.2
214	21.3	11.4	6.3	1.9
215	23.3	9.0	6.2	1.3
216	20.1	5.1	5.9	1.0
217	17.6	3.2	5.0	0.8
218	15.6	2.4	5.7	0.6
219	17.6	2.3	5.2	0.5
220	20.0	1.9	5.8	0.5

[a] Water deficit period from day of year 208–220

Table 2. Consumptive use (ET) of the soybean crop calculated from changes in the soil water content (0–60 cm depth) between irrigations for the well-watered (Control) and the water-stressed (Stress) treatments in 1991

Treatment	Period (day of year)	Number of days	Extracted soil water (cm^3 cm^{-3})	Mean ET (mm d^{-1})	Standard deviation (mm d^{-1})
Control	171–177	7	0.035	3.0	1.0
	180–183	4	0.028	4.2	1.3
	186–189	4	0.029	4.4	0.8
	213	1	0.013	7.8	1.7
	216–217	2	0.021	6.3	1.3
Stress[a]	211–212	2	0.024	7.2	1.4
	213–216	4	0.019	2.9	0.5
	217–220	4	0.006	0.9	0.1

[a] Water deficit period from day of year 208–220

The calculation of the consumptive use of the soybean crop and the simulated transpiration results indicated that the flow gauges used in this study overestimated plant water loss under the prevailing conditions. To examine possible sources of error which can arise from the stem heat balance method, a sensitivity analysis was made (Table 3). The SHB method was most sensitive to changes in the heater resistance (R in Eq (2)) of the gauge. An increase in R by 10% resulted in a 17.4% decrease in sap flow. However, the sensitivity analysis demonstrated that even large errors in a particular input parameter of

Table 3. Sensitivity analysis for the sap flow measurements with respect to modified input parameters. The analysis is based on results from a Dynamax SGA10 gauge installation on day of year 210 in 1991

Modified parameter (P)	P-change (%)	Sap flow (F) ($g\,d^{-1}$)	F-change (%)
K_g ($W\,mV^{-1}$)[a]			
0.745	0.0	565.0	0.0
0.820	+10.0	518.7	−8.2
0.671	−10.0	777.0	+37.5[b]
Stem area (cm^2)			
0.636	0.0	565.0	0.0
0.785	+23.4	543.1	−3.9
0.950	+49.4	526.5	−6.8
1.131	+77.8	510.0	−9.7
Heater resistance (Ω)			
112.0	0.0	565.0	0.0
123.2	+10.0	466.5	−17.4
100.8	−10.0	894.2	+58.3[b]
K_s ($W\,m^{-1}\,K^{-1}$)[c]			
0.54[d]	0.0	565.0	0.0
0.59	+10.0	554.7	−1.8
0.49	−10.0	580.7	+2.8
0.42[e]	−22.2	616.7	+9.2

[a] K_g – thermal conductance constant for a particular gauge installation, [b] unrealistic because of calculated sap flow also at night, [c] K_s – thermal conductivity of the stem, [d] herbaceous plants (Sakuratani 1984), [e] woody plants (Sakuratani 1984)

±10% or more, which are unlikely, did not modify the calculated sap flow to more acceptable values.

Shackel et al. (1992) used the SHB method to measure transpirational sap flow on three-year-old peach trees under field conditions. They reported that in some cases, errors in sap flow approached two orders of magnitude as a result of very small and sometimes negative temperature differentials (dT) between the stem surface temperature above and below the gauge heater. These authors suggested that the effect of ambient conditions on gauge signals should be critically evaluated before considering heat balance estimates of sap flow as reliable under any given conditions. Baker and Nieber (1989) also recognized that dT is critical in the calculation of sap flow.

A very low dT may cause overestimations of sap flow as dT is part of the denominator in Eq. (7). However, Fig. 3 demonstrates that dT during the measurement period of this study was generally in the recommended range of 0.2 °C to 8 °C. In the morning, dT should not exceed 8 °C and during the peak flow period dT should be above 0.2 °C (Van Bavel and Van Bavel 1990).

The course of the stem surface temperature dT versus sap flow rate is shown in Fig. 4 for two gauges on different soybean plants. As would be expected, dT declined with increasing heat transfer by convection. To avoid ambient effects on the temperature regime of the gauges, a weather shield kit was used. Moreover, gauges were well-shaded by the soybean canopy, so that an error in dT seems unlikely for the sap flow determinations reported in this research. Figure 5 shows the heat balance of a SGA10 gauge installation on a soybean stem. The distribution of

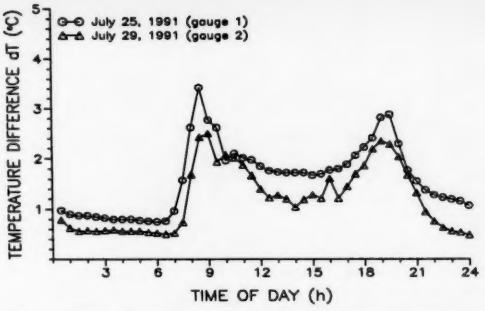

Fig. 3. Diurnal variations of the stem surface temperature dT above and below the heater. Data from two gauge installations (model SGA10) on different soybean plants

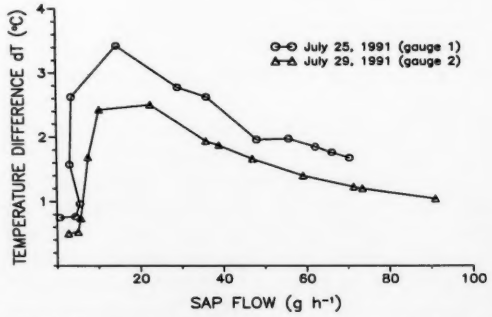

Fig. 4. Temperature difference dT at the stem surface versus sap flow rate. Data from two gauge installations (model SGA10) on different soybean plants

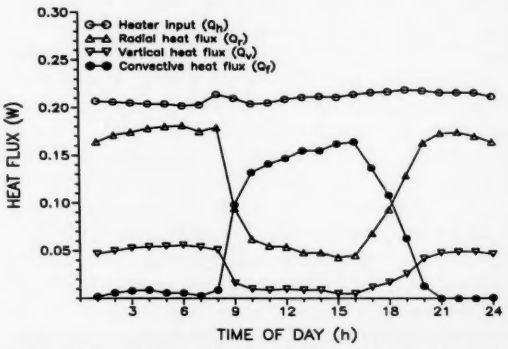

Fig. 5. Diurnal course of heat distribution on a soybean stem. Data from a SGA10 sap flow gauge on August 15, 1991

the heat supplied was reasonable and in good agreement with the energy balance of a gauge installation on Red Cedar described by Van Bavel and Van Bavel (1990).

Another possible reason for the overestimation of crop transpiration by sap flow measurements was given by Ham et al. (1990). They reported that their experimental plot included many cotton plants that were much smaller than those used for sap flow measurements. Converting the sap flow per plant to crop transpiration by multiplying by the plant density, resulted in a 63% larger

value than the value obtained by normalizing sap flow measurements by leaf area. Ham et al. (1990) suggested that in the case of a variable plant size within the canopy, the sap flow per plant and day should be divided by the leaf area per plant and then multiplied by the mean leaf area index of the plot. However, in this study the soybean canopy in the sap flow measurement area was quite homogeneous and no pronounced differences in plant size were detected. Moreover, the relative good agreement among the replications of the sap flow measurements indicated that variable plant sizes were not the reason for the overestimation of soybean crop transpiration by the SGA10 flow gauges in the present work.

The sensors used in this study were designed for herbaceous plants with a stem diameter of 9 to 12 mm. The width of the resistance heater was 10 mm and the energy input for all gauges ranged from 0.10 to 0.25 W. Ham and Heilman (1990) tested similar sap flow gauges on sunflower and found that transpiration was constantly overestimated during periods of high sap flow. Adjusting the power to the stem did not improve gauge performance at high flow rates. However, increasing the heater width greatly improved gauge performance. The relationship beween stem diameter and size of the heated segment is important for the gauge design (Ham and Heilman 1990). According to Sakuratani (1981), the heater width may be two times larger than the diameter of the stem. Possibly, the SGA10 sap flow gauges in the present work overestimated soybean transpiration because the heater was too narrow (equal to the stem diameter) and the power distribution of the gauges may not have been suitable for a outdoor installation on soybeans.

Conclusions

The stem heat balance technique is a non-destructive method, suitable for measuring the xylem sap flow of intact herbaceous and woody plants. Sap flow gauges responded quickly to changes in the environmental conditions (solar radiation, water supply). However, soybean crop transpiration calculated from field-measured sap flow data differed markedly from crop water use determined by changes in the soil water content and simulated transpiration by the locally calibrated SOYGRO model. It is possible that the heater width of the Dynamax SGA10 gauges was not appropriate for measuring the soybean transpiration rate in the field. Currently, the stem heat balance method has not often been examined under field conditions. Further investigations are required to detect the critical operation range of this new technique.

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A comparison of soil- and canopy temperature-based methods for the early detection of water stress in a simulated patch of pasture

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Abstract. This paper evaluates the sensitivity of two different methods of water stress detection in a simulated patch of pasture grown in a greenhouse. The performance of two indices, based respectively on canopy temperature and soil water content values – the latter gauged by means of a time domain reflectometry (TDR) system, was assessed against actual evapotranspiration, measured by a very accurate weighing system. Both methods were able to detect water shortage by the time transpiration was reduced to some 80% of its potential value. The soil-based index, however, relied on the estimate of root water extraction rate, which may not be known. It is concluded that detection of water shortage by means of a canopy temperature-based stress index is to be preferred to measuring soil water deficits by time domain reflectometry, despite the accuracy of the TDR-based soil water content estimate.

Introduction

Although there is little doubt that maximum yields are only achieved under conditions of non-limiting water supply, the question how early a water shortage is to be detected in order to avoid a significant decline in productivity is still an open one. As far as pasture is concerned, Krist and Snijders (1987), summarizing several years of experiments with grassland in The Netherlands, concluded that yield reduction per mm potential moisture shortage could vary from some 18 kg dry matter ha^{-1} on clay soil, to more than 30 kg ha^{-1} on sandy soil. It would seem, therefore, that optimum water management, at least for pasture, requires water stress detection to be as timely as is technically feasible.

As the research described here was a part of the development of a farm management information system, we confined ourselves to testing stress detection by means suitable for remote operation. For many years soil water content has been measured by either manual or inaccurate methods, so that soil based stress detection methods did not provide a feasible alternative to the canopy-temperature based stress indices now widely used. Time-domain reflectometry, TDR, (Topp et al. 1980), however, has proven to be an easily automated and accurate means for measuring soil water content, so that a TDR-based remote stress detection is presently feasible.

The principle underlying canopy temperature-based stress detection is simple: plants not adequately supplied with water will transpire less than well-watered plants, and hence will be warmer than their well-watered counterparts. Detection of water stress by this means, however, implies both that the temperature of an otherwise similar, well-watered plot be known and that the deviation of temperature from this "ideal" value can be detected with sufficient accuracy, two conditions not easily met.

Soil-based detection of water shortage, on the other hand, is based on the observation that it is increasingly difficult for a crop to extract water from the soil beyond a threshold pressure head. However, recognition of water shortage by this means requires that this threshold value be known, which is not trivial either.

Accordingly, both methods have potential shortcomings, so that it was thought worthwhile to test their accuracy in the present study.

Temperature-based stress index

From the coupling of the energy balance equation to the transfer equations for both sensible and latent heat, an expression for the temperature difference between the canopy and the air can be derived (e.g. Monteith 1981):

$$T_c - T_a = \frac{\frac{r_a + r_c}{\varrho_a c_p}(R_n - G) - \frac{D}{\gamma}}{1 + \varepsilon + \frac{r_c}{r_a}}. \qquad \text{K (1)}$$

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where T is temperature (K) and the subscripts c and a refer to the canopy and air, respectively; R_n is the net flux density of radiation ($W\,m^{-2}$); G is the flux density of sensible heat transferred into the soil ($W\,m^{-2}$); D is vapour pressure deficit of air (Pa); r_a and r_c ($s\,m^{-1}$) are the boundary layer (aerodynamic) resistance and the canopy resistance, respectively. Furthermore, $\varrho_a c_p$ is the volumetric heat capacity of air ($J\,m^{-3}\,K^{-1}$); ε is the rate of change of latent heat content with sensible heat content of air saturated at present temperature and γ is the thermodynamic psychrometric constant ($Pa\,K^{-1}$).

Jackson (1982), reviewing previous literature, concluded that the effect of wind on canopy temperature, implicit in the boundary layer resistance, is likely to be minor (at least for winds not too strong), a contention supported for pasture under cloudy humid conditions by the experimental results of Feldhake and Edwards (1992). Hence, temperature of a vegetated canopy is affected primarily by three climate factors: air humidity, net radiation balance and air temperature; if, and only if, a high correlation exists among radiation, temperature and humidity, the number of climate variables affecting canopy temperature could be reduced, possibly, to one – as proposed by Idso (1982) with his non-water-stressed baseline approach. In variable climates the influence of individual weather factors needs to be taken into account, as concluded by Smith et al. (1986), for instance, from an experiment in New South Wales. Fuchs (1990) confirmed "that the detection of water stress by a canopy temperature measurement must account for the effects of meterological factors on the energy balance of the foliage".

A method satisfying this requirement was proposed by Jackson et al. (1981), who introduced a crop water stress index (*CWSI*) as follows. The highest possible temperature a canopy can achieve (T_M) is given by:

$$T_M \equiv \lim_{r_c \to \infty} T_c = T_a + \frac{r_a}{\varrho_a c_p}(R_n - G). \qquad \text{K (2)}$$

There is, on the other hand, also a lower limit (T_m) to canopy temperature, that is achieved for a minimal canopy resistance (r_m):

$$T_m \equiv \lim_{r_c \to r_m} T_c = T_a + \frac{\frac{r_a + r_m}{\varrho_a c_p}(R_n - G) - \frac{D}{\gamma}}{1 + \varepsilon + \frac{r_m}{r_a}}. \qquad \text{K (3)}$$

Then, varying climatic conditions can be accounted for by using the difference $T_M - T_m$ as the reference against which deviations of the measured canopy temperature from the "unstressed" temperature T_m have to be gauged. Namely:

$$CWSI \equiv \frac{T_c - T_m}{T_M - T_m}. \qquad -(4)$$

Equation (4) can be calculated from Eqs. (1), (2) and (3), by eliminating $(R_n - G)$, assuming this to be an independent variable, although strictly speaking it is not. The crop water stress index can then be written as an explicit function of canopy resistance, or of the ratio of actual to potential transpiration:

$$CWSI = \frac{r_c - r_m}{(1 + \varepsilon) r_a + r_c} = 1 - \frac{E}{E_p}. \qquad -(5)$$

where E is calculated by the Penman-Monteith equation:

$$E = \frac{\varepsilon r_a (R_n - G) + \varrho_a c_p D/\gamma}{L[(1 + \varepsilon) r_a + r_c]}. \qquad kg\,m^{-2}\,s^{-1} \text{ (6)}$$

L being latent heat of evaporation of water. Potential transpiration (E_p) is calculated by Eq. (6) with $r_c = r_m$.

Applying this "big-leaf" model to detect stress, obviously assumes that the canopy temperature that is measured is the one temperature defined by such a model – a requirement that may be hard to satisfy for many crops that are tall or have incomplete cover (Fuchs 1990), but one that grass is likely to meet. Moreover, Jackson's et al. (1981) original definition of *CWSI* referred to the special case that r_m is zero, with the minor consequence that the stress index of a non-wet canopy, however well watered, is larger than zero; the minimal canopy resistance is known to be species-specific (Körner et al. 1979). At the other extreme, T_M is also a theoretical upper limit to canopy temperature that will never be reached. This because actual net radiation would become significantly smaller than R_n, as r_c increased, due to thermal radiation from the canopy, as Stanghellini (1987) and Paw U and Gao (1988) have shown. Moreover, Jackson and Ezra (1985) demonstrated that the albedo of leaves could increase, and thus net radiation decrease, in consequence of water stress. Net radiation is also reduced by drooping or curling of leaves, a common plant response to water stress, also likely to affect r_a. The stress index of plants wholly deprived of water, therefore, can still be less than one, when calculated by means of Eq. (4). However, as the main purpose of this application is early detection of water stress, this would appear to be of little consequence.

Soil-based stress index

Shortage of water takes place, by definition, when the amount of water extracted from the soil does not match potential transpiration. This trivial observation allows a soil-based "stress index" to be derived, as follows. Extraction can be represented (e.g. Feddes et al. 1978) as a sink term S, defined by:

$$S = \alpha(h)\, S_M \qquad d^{-1} \text{ (7)}$$

where S is water extraction rate $cm^3_{H_2O}\,cm^{-3}_{soil}\,d^{-1}$; α is a non-dimensional function of soil water pressure head h, contained between 0 and 1; and S_M is the maximum possible water extraction by plant roots defined by:

$$S_M = E_p / |z_r| \qquad d^{-1} \text{ (8)}$$

where E_p is the potential transpiration rate ($cm\,d^{-1}$) and z_r (cm) the effective rooting depth, defined as the depth up to which approximately 75% of the roots are found.

Obviously, the integral of the sink term over the effective rooting depth has to be equal to the actual transpiration rate of the crop E (cm d^{-1}):

$$E = \int_0^{|z_r|} S \, dz. \qquad \text{cm d}^{-1} \quad (9)$$

And, for transpiration to attain its potential value, S has to equal S_M and $\alpha(h)$ must be unity; on the other hand, under non-optimal conditions, S_M is reduced by means of the pressure-head-dependent function α. Both S_M and the shape of $\alpha(h)$ are commonly assumed not to vary throughout the profile; a very useful, although crude, simplification which implies that:

$$\alpha(h) = E/E_p = 1 - CWSI. \qquad - \quad (10)$$

Hence, insofar as the function $\alpha(h)$ is known, soil water pressure head is as good a stress indicator as CWSI. We will show in the following, that lack of information about the function α, and not the accuracy of the soil water content assessment, is the factor limiting the reliability of the soil-based stress indicator, for incipient water shortage.

Materials and methods

To assess the suitability of both methods of stress detection, an experiment was carried out on a simulated sward of perennial ryegrass (*Lolium perenne*) growing on a weighing lysimeter placed in a glasshouse. The glasshouse was single-glass, four span, and E – W oriented. The ventilation windows facing north were kept constantly open, no artificial heating or lighting being provided. The grass was grown in a box (0.8 by 0.7 m and 1 m deep) filled with sandy soil and completely surrounded by a guard area, where a similar sward was grown. The box was connected with a water tank in a way that allowed the depth of the ground water table to be detected and regulated. The walls of the box and of the tank, as well as the pipes connecting them, were insulated in order to reduce heat exchange with the surrounding environment. One face of the box was an acrylic plate so that, upon removal of the insulating material, rooting depth could be observed. The electronic balance on which both the box and the tank were placed, allowed detection of weight variations with an accuracy of 2.5 g on a total load of 1 500 kg. The grass was mown about once a month, when the mean sward height was about 25 cm.

Climate variables measured were: incoming shortwave radiation and net radiation, respectively, by a solarimeter and a net radiometer, both placed about 40 cm above the grass. Air temperature and humidity by a thermohygrometer placed at a height of about 30 cm, with a solid state device for humidity measurement and a platinum resistance for temperature measurement. Radiative temperature of the canopy was determined by an infrared thermometer with a field of view of about 2°, placed 70 cm above the crop. All measurements were performed at 5-minute intervals by a data-logger.

Other parameters estimated were: aerodynamic resistance was determined by inverting the heat transfer equation, wherein sensible heat flux was calculated through the energy balance equation. This procedure is likely to be affected by large errors whenever sensible heat flux is small, that is, whenever transpiration and net radiation are of similar magnitude, and, indeed, the standard error of the estimate of r_a approached often 100%. Nevertheless, since meaningful variations of the boundary layer resistance in a closed environment are expected to be small, its mean value of 65 s m^{-1} was used throughout. Minimal canopy resistance (r_m) was also taken as 65 s m^{-1}, as proposed for clipped grass by a recent revision of F.A.O. guidelines (Smith 1991). Heat flux into the soil (G) was assumed to be a constant one-tenth of net radiation, as proposed by De Bruin and Holtslag (1982); the results proved to be rather intensitive to this assumption.

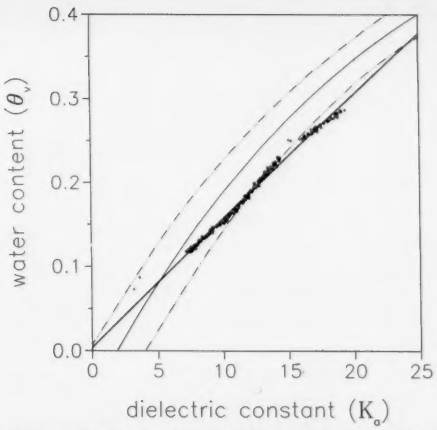

Fig. 1. Calibration data for the TDR-probe. The thick line represents the fitted Eq. (11). The thin line, Topp's equation for mineral soils, with 95% confidence limits (broken lines)

The profile of soil water content in the box was determined through a TDR-system, equipped with six three-wires probes, placed horizontally at depths of 5, 10, 20, 30, 45 and 60 cm, respectively. The relationship between measured dielectric constant (K_a) and volumetric water content of the soil (θ_v, cm^3 cm^{-3}) was determined by comparing K_a values with gravimetrically determined θ_v measurements of drying samples of the soil, that was 90.5% sand (particle size between 50 and 2 000 μm) and the rest finer material (smaller than 50 μm); with 3% organic material. The 275 points calibration, shown in Fig. 1, are best-fitted by:

$$\theta_v = 3.99\,10^{-3} + 1.55\,10^{-2}\,K_a - 1.48\,10^{-5}\,K_a^2 - 3.14\,10^{-7}\,K_a^3 \qquad - \quad (11)$$

with a standard error of the estimate of θ_v of about 0.5%. Most data fall just within the 95% confidence band of Topp's et al. 1980 best-fit line for mineral soils. However, Topp et al. (1980) attributed most of their variance to differences in soil type, density or salinity, that may have played a role here, rather than to experimental errors. For instance, both Nadler et al. (1991) and Amato et al. (1993) derived calibration curves for mineral soils similar, yet not identical, to Topp's original curve. The relationship between volumetric soil water content and pressure head (h), was determined according to the standardized Dutch "Staring" series – Wösten et al. (1987):

$$|h| = 9.47\,10^5\,\theta_v^8 - 1.75\,10^6\,\theta_v^7 + 1.38\,10^6\,\theta_v^6 - 6.00\,10^5\,\theta_v^5 + 1.58\,10^5\,\theta_v^4 - 2.57\,10^4\,\theta_v^3 + 2.52\,10^3\,\theta_v^2 - 1.38\,10^2\,\theta + 3.30. \qquad \text{MPa} \quad (12)$$

Irrigation took place about once a week, by refilling the amount of water lost by evapotranspiration; as the water table was kept constantly at 70 cm depth, h values of the upper soil layer down to 30 cm, in which the largest part by far of the rooting system was found, did not change much: they varied approximately from 12 kPa soon after an irrigation to 40 kPa before the next one.

After collecting reference data for about one month, the method was tested during a dry period of a couple of weeks, starting from May 17. For this purpose both irrigation and ground water table control were suspended 15 days after a sward cut. The water table dropped slightly, to 72 cm in two weeks. Figure 2 shows the profile of θ_v the day after the last irrigation and two weeks afterwards. The difference in soil water content, calculated as the difference between the integral of the two polynomial relationships fitted to the data,

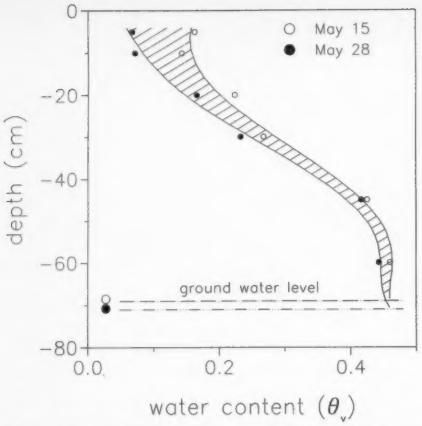

Fig. 2. The profile of θ_v (volumetric soil water content) the day after the last irrigation and two weeks later; points represent data. A water content at saturation equal to the highest measured value was assumed in order to fit the polynomial relationships shown

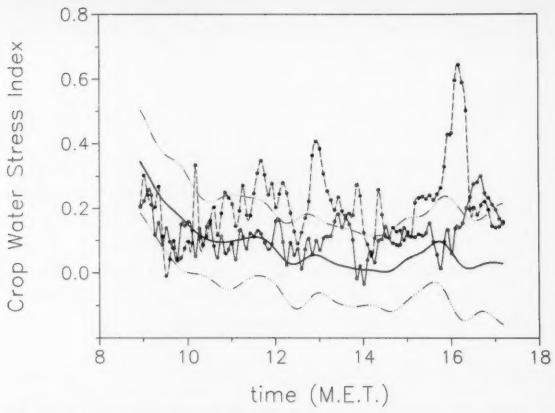

Fig. 3. Mean daily trend of *CWSI* for the reference period (thick line) and the plus and minus one-standard-deviation bands (broken lines). *CWSI* sets of two days are shown as examples: one, May 19, open circles, not significantly different from the reference and another, May 24, closed circles, significantly higher (confidence level 1‰)

indicated by the shaded area in Fig. 2 was 15.8 kg, whereas decrease in weight during the same interval was 15.9 kg. Such an agreement has to be fortuitous, given the inaccuracy of the estimate of soil water content at saturation and of the profile demarcations. With respect to the latter, linear interpolation between data points in Fig. 2 would have resulted in an estimated water content decrease of 14.7 kg which, nonetheless, sanctions the reliability of the present measurements of volumetric soil water content.

Results

Temperature-based water stress detection

Jackson et al. (1981) calculated the *CWSI* from eight measurements around 2 p.m. More data, however, could smooth out the effect of intermittent cloudiness on canopy resistance, as the latter is assumed to be constant. Accordingly, one hundred *CWSI* values were calculated daily from as many measurements centred at 1 p.m. (M.E.T.). A reference *CWSI* set was then assembled by averaging concurrent data collected during the 32 days preceding, and the three following, the last irrigation. A set of one hundred *CWSI* values was calculated similarly for each day of the subsequent dry period and a two-sample *t*-test was performed to detect daily significant deviations from the reference sample, as shown in Fig. 3.

Mean daily ratio of actual to potential transpiration during the reference period was 0.97, with a standard deviation, $\sigma = 0.12$. Mean *CWSI*, on the other hand, was 0.07 with $\sigma = 0.06$. Figure 4 depicts mean daily value of *CWSI*, for each day of the dry period as a function of reduction in transpiration, the solid symbols referring to *CWSI* sets significantly different (confidence level 1‰) from the reference set. Means of the above mentioned reference set are shown by a larger symbol with standard deviation bars.

If the admittedly arbitrary criterion had been adopted that water shortage is proven by two consecutive samples

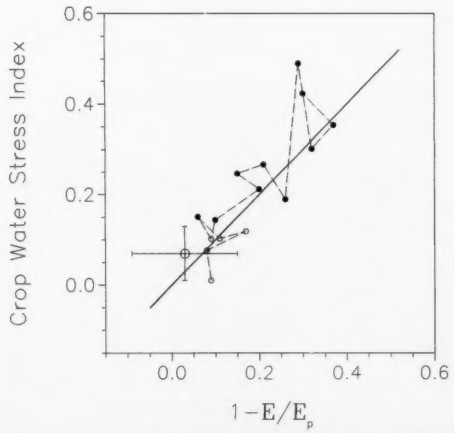

Fig. 4. Mean daily *CWSI* as related to the reduction in transpiration during the dry period. The larger symbol represents the mean values for the reference period, with standard deviation bars. Consecutive days are connected, starting from May 17, lower left. Filled symbols refer to days whose *CWSI* set deviated significantly from the reference sample, as explained in the text

of *CWSI* being significantly larger than the reference, then irrigation would have been given on May 24, that is 10 days after the previous water application, some 22 and 28 mm actual and potential transpiration, respectively, having elapsed. The same result could have been achieved both by similarly applying Jackson's definition of *CWSI*, that is by assuming $r_m = 0$, and by using a more complex (radiation-dependent) model of r_c, as shown by Stanghellini et al. (1992). One may conclude, therefore, that a mean daily pattern of reference *CWSI*, sufficiently accounts for weather variations, although it might be argued that a shorter time interval could have been considered as well.

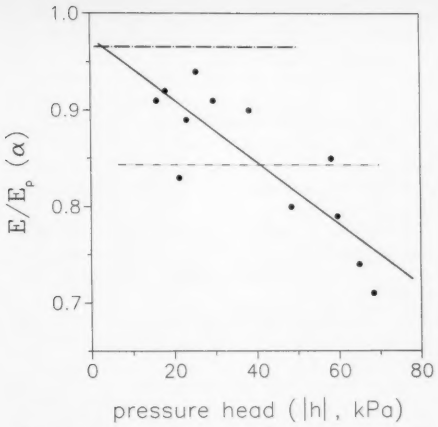

Fig. 5. Measured α (that is, E/E_p) as related to the soil water pressure head, h, for each day of the dry period, from May 17 (left) to May 28 (right). The full line is that of best-fit, whereas the horizontal lines represent the mean value of α for the whole reference period (dash-point) and its standard deviation (broken line)

Soil-based water stress detection

The function $\alpha(h)$ is shown in Fig. 5: the points represent estimates of α as the ratio of actual to potential transpiration, Eq. (10), corresponding soil water pressure heads being determined from θ_v data (down to 30 cm) by means of Eq. (12). One could stipulate that extraction is significantly reduced, that is, $\alpha(h)$ is significantly smaller than unity, as soon as the ratio E/E_p falls below its mean value minus σ, that is 0.85, which is the value for $|h|$ equal to 40 kPa, according to the best-fit line shown in Fig. 5. Hence, irrigation would have been given by May 24 also by this method, although this would require an independent independent knowledge of the best-fit line.

The literature would not be of much help in providing this information: De Jong and Kabat (1990), for instance, could quantify the "limiting point" (that is the pressure head at which extraction starts to decrease) no better than between 20 and 80 kPa for grass on sandy soil. Our best-fit line, moreover, would extrapolate to a relatively small absolute value (300 kPa) of the wilting pressure head, whereas published values for grass vary between 400 and 800 kPa; Belmans et al. (1984) having contributed the former and De Jong and Kabat (1990), the latter. In fact, this lack of precision is not surprising: in all experiments, including our own, a profile has to be contrived from the sparse data available within the rooting depth, the latter being, for good measure, also coarsely estimated. Stanghellini et al. (1992) have shown that, in consequence of both these factors, the error on the horizontal position of data points such as in Fig. 5 becomes more relevant as h increases. Altogether, it is unlikely that a literature-derived relationship between α and h can be reliably applied to particular conditions for the early recognition of water shortage, despite the accuracy of the estimate of soil water content, demonstrated in this experiment.

Conclusion

The main conclusion to be drawn is that infrared temperature-based stress indices are more likely to be suitable for early detection of water shortage than soil based methods. Similarly, Itier et al. (1990), arguing that predawn leaf water potential could be used as a good stress indicator in tomatoes, claimed that soil water content could not. By other means, Peñuelas et al. (1992) working with greenhouse strawberries subject to two mildly stressing treatments, concluded that most variations on the *CWSI* theme were more reliable than soil water content-based indicators.

On the other hand, it is known that protracted water shortage can induce morphological modifications restoring the balance between water extraction and transpiration by less damaging means than stomatal closure (Hsiao, 1993). Accordingly, sustained stress may reduce the effectiveness of infrared thermometry (De Lorenzi et al. 1993), whereas the impact of the inaccuracy of the soil-based stress indicator would decrease.

Acknowledgements. This work was largely carried out when Francesca De Lorenzi was on leave at IMAG-DLO in Wageningen; financial support was provided both from Nuffic and IMAG-DLO. A.H. Bosma's advice, encouragement and support are gratefully acknowledged. Thanks are due to C. Werkhoven for assistance with both the TDR and the data-logger, to J.G. Cornelissen and to T. Postma, A.P. Verkaik and P.C.J. Gabriëls for their collaboration during the measurements.

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Chloride accumulation and partitioning in Barley as affected by differential root and foliar salt absorption under saline sprinkler irrigation

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Abstract. Barley is a crop that has been classified as tolerant to soil salinity, but under sprinkler irrigation with saline water it can readily absorb salts through its leaves and develop injury. Experiments using a triple-line-source sprinkler system were conducted on barley between 1989 and 1991 to determine: (1) the specific effects of foliage wetting on the mass of different shoot components; (2) the relative contribution of root and foliar absorption processes to foliar Cl accumulation; and (3) the extent by which these processes affect Cl partitioning in the shoot at the end of the season. Some plants were covered with plastic during the irrigation process to prevent foliar wetting while others remained uncovered. Salinity affected the partitioning of dry matter in the shoots regardless of whether plants were covered during the irrigation process. The organs associated with reproduction, e.g., heads and peduncles, comprised a larger fraction of the total shoot biomass under high salinity than under low salinity, indicating that plants under salinity stress were able to redistribute their dry matter to favor reproductive growth. The Cl concentration of the young leaves sampled from uncovered plants was linearly related (i.e., $r^2 > 0.71$) to the Cl concentration of the irrigation water. Equivalent leaves from covered plants also contained a substantial amount of Cl but concentrations were weakly correlated (i.e., $r^2 \leq 0.41$) with the concentration of Cl in the irrigation water. At low salinity, there were no differences in leaf Cl concentrations between covered and uncovered treatments. In young leaves, differences between these treatments progressively increased with increasing salinity, indicating that the relative contribution of Cl in the leaf from foliar absorbed salts increased with increasing Cl in the irrigation water. Only in the youngest leaves sampled at the end of the season from plants grown at high salinity was the Cl concentration in uncovered plants (foliar plus root-absorbed Cl) found to be more than twice that in covered plants (only root-absorbed Cl) indicating that most of the Cl in young leaves originated from foliar absorption. In addition, only in the youngest leaves (e.g., flag leaves) was the slope of the relationship between leaf-Cl concentration and Cl concentration of the sprinkling water of uncovered plants more than twice that of covered plants, also indicating that foliar-Cl absorption was more substantial than root-Cl absorption. At high salinity, the difference in leaf Cl concentration between covered and uncovered plants was maximum in the youngest leaf (flag leaf), but differences became progressively smaller with increasing leaf age until ultimately concentrations of chloride in leaves older than the flag leaf-2 were highest in covered plants. In older tissue, it was difficult to distinguish which process, foliar or root absorption, was most responsible for leaf-Cl accumulation. These processes may not be entirely independent of one another and much of the Cl in the oldest leaves of uncovered plants could have been derived from foliar sources during the first month of sprinkling, reaching maximal levels, and thereby restricting root-absorbed Cl. Furthermore, since these leaves at the end of the season are more injured and drier than those from covered plants, late-season sprinkler irrigations may have been responsible for leaching some of the Cl out of these necrotic leaves.

Sprinkler irrigation with saline water often decreases the yield of the crop more than if the same water is applied by surface or drip irrigation methods (Bernstein and Francois 1973, 1975; Gornat et al. 1973; Meiri et al. 1982). This is not surprising since many crops under sprinkler irrigation absorb salts directly through their leaves and suffer foliar injury (Bernstein and Francois 1975; Busch and Turner 1967; Ehlig and Bernstein 1959; Francois and Clark 1979; Gornat et al. 1973; Harding et al. 1958; Maas et al. 1982a, b). Although foliar salt accumulation and injury has been considered to be a major cause of this yield reduction, no information is available to predict

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yield losses as a function of salt concentration of the sprinkling water (Maas 1985). Foliar injury from saline sprinkling water, however, may not always translate into a yield reduction. Injury produced on many annual crops from six weeks of sprinkler irrigation in a greenhouse using water with an EC of 1.5 to 6.0 dS/m did not reduce yields below those of uninjured controls (Maas et al. 1982b). In another case, plum trees sprinkled one season with saline water produced severe foliar injury but yields were not affected (Mantell et al. 1989). In the subsequent year, however, yields were reduced because of a decrease in fruit-set, even though sprinkling with saline water was discontinued.

Plants that are sprinkle irrigated with saline water can accumulate salt in their leaves by two processes: (1) by root absorption and subsequent translocation to the leaves; and (2) by direct foliar absorption. Root absorption is a rather selective process and most crop plants are relatively effective at excluding much of the salts in the soil solution (i.e., Cl and to a larger extent Na) from entering the leaves. The absorption of salts by leaves is less selective (Aragüés et al. 1994) and Na and Cl in the sprinkling water can enter the leaf in proportion to their concentration (Maas et al. 1982a, b). Therefore the advantage of ion-selective processes that the plant root has acquired through evolution may be lost under sprinkler irrigation (Grattan 1993).

Susceptibility to foliar injury varies among crops but not necessarily in strict relation to the rate of foliar salt-absorption (Maas et al. 1982b; Maas 1985). Tree crops, for example, are known to be susceptible to specific-ion toxicities when grown in saline soils (Maas 1990), but were found to vary in their sensitivity to sprinkler-applied salt solutions (Ehlig and Bernstein 1959). Leaves of deciduous tree crops (almond, apricot, and plum) and orange absorbed substantial amounts of Na and Cl and were severely damaged by saline sprinkling water whereas those from avocado, which absorbed Na and Cl more slowly, were not damaged. Most annual crops are not normally susceptible to specific-ion toxicities but can be particularly sensitive if sprinkle irrigated with saline water (Bernstein and Francois 1975; Gornat et al. 1973; Maas et al. 1982a, b). Tomato and potato readily absorbed Na and Cl into their leaves under sprinkler irrigation with saline water and were severely injured whereas sorghum and cauliflower absorbed salts in their leaves more slowly and were only slightly injured. Safflower, on the other hand, readily absorbed salts by its leaves but was only slightly injured.

Experiments at the US Salinity Laboratory showed that Na and Cl absorption by leaves from many herbaceous crops, including barley, were not only linear functions of the hours sprinkled (Maas et al. 1982a, b) but that increased irrigation frequency contributed more to foliar salt accumulation than increased sprinkler duration (Maas et al. 1982a). Although these greenhouse experiments were useful in distinguishing sensitivities among different crops to saline sprinkling water, they were not designed to determine the relative contribution of root- and foliar-absorption processes to foliar-Cl accumulation or to determine what impacts these absorption processes have individually, and collectively, on crop yield in field conditions.

The experiments described here used a triple line-source sprinkler system developed and tested by Aragüés et al. (1992) to: (1) evaluate the specific effects of foliage wetting on the biomass of different shoot components; (2) determine the relative contribution of root and foliar absorption processes to foliar Cl accumulation in field-grown barley; and (3) determine the extent to which these absorption processes affect Cl partitioning in the shoot at the end of the season.

Materials and methods

The triple-line-source sprinkler (TLS) system at the Servicio de Investigacion Agraria (SIA) field experimental site in Zaragoza, Spain, described in detail by Aragüés et al. (1992), was used for our study. Three parallel sprinkler laterals were spaced 15 m apart, a distance equivalent to the wetted radius of a sprinkler. Sprinklers along the lateral were spaced 4.5 m apart. The center line discharged saline water while the outer lines discharged low-saline water. This arrangement produced a linear salinity gradient between the center and outer laterals while providing an even distribution of water (irrigation uniformity >90%). Minimum and maximum EC values and major-ion concentrations in the applied water for each season are presented in Table 1.

Irrigations were scheduled according to evapotranspiration estimates over a 10-d period from pan evaporation data and site-specific crop-coefficients for non-stressed barley. Experimental plots were irrigated two to three times per week for 30 to 36 min per irrigation. The total number of irrigations throughout the experimental period in 1989, 1990, and 1991 were 34, 29, and 31 and the total quantity of water applied by sprinkling was 400, 417, and 406 mm, respectively. In addition, plots received 151, 102 and 127 mm of rain during the 1989, 1990, and 1991 season. All three sprinkler laterals were supplied with low salinity water for an additional three-minute period at the end of each irrigation to remove saline water from the leaf surface and to reduce additional foliar salt absorption and injury. This post-irrigation, leaf-rinsing technique was also used by Frenkel et al. (1990) as a means of minimizing leaf burn. In 1991, a 3-min pre-irrigation with low saline water was also given as a means of reducing foliar absorption.

Table 1. Minimum and maximum EC values (dS/m) and ion concentrations (mmol/l) of the applied water

	Year		
	1989	1990	1991
Minimum values [+]			
EC	2.5	2.5	1.6
Cl	10.5	10.5	6.6
Na	8.9	8.9	5.6
Ca	5.5	5.5	3.8
Maximum values [+]			
EC	16.3	17.2	14.7
Cl	162	173	169
Na	62	65	74
Ca	57	60	52

[+] Time and volume weighted average values that include both sprinkling and rain water. Minimum and maximum values reflect the composition of the applied water at the farthest and closest pluviometer from the center line

Barley (*Hordeum vulgare* L.) seeds were sown in rows parallel to the sprinkler laterals on 22 Dec. 1988, 20 Jan. 1990 and 19 Nov. 1990 and were harvested on 29 June 1989, 28 June 1990, and 1 July 1991, respectively. In 1989, four Winter cultivars were tested; 'Albacete', 'Barbarrosa', 'Criter', and 'Igri'. In 1990, four Spring cultivars ('Georgie', 'Hassan', 'Patty', and 'Trait D'Union') were tested since heavy rains in Nov. and Dec. 1989 delayed access to the field until Jan. 20; a date considered too late to re-plant the same Winter cultivars. Since no significant differences in leaf Cl accumulation were found among cultivars in either 1989 or 1990, only 'Albacete' was studied in 1991. The loam soil at the experimental site was classified as a mixed, mesic, Typic Torrifluvent. Barley stands were established by sprinkler irrigation with low-saline water until plants were at a suitable age to begin the saline sprinkling water treatments. Five locations, each 2.8 m apart, at increasing distances from each side of the central lateral were designated as plots to sample leaves and plants. Plots at each sampling location were 1.2 m in length and 1.4 m wide. Pluviometers were situated in each of the five plots on both sides of the central lateral to measure water quantity and to monitor EC. In 1989 and 1990, two of the four cultivars tested were planted on one side of the central (saline) lateral while the other two were planted on the other side. Before sprinkling with saline water began, some of the barley plants in each of the designated plots were covered with transparent plastic during irrigations to avoid foliar wetting during the irrigation process but allowing the soil under the covered plants to become salinized. All other plants that were tested remained uncovered. Soil borders at the perimeters of each plot assured that the sprinkling water applied to the plot was contained within the plot. In 1990, however, plants in covered treatments were covered at all times with a transparent, corrugated plastic-roof. Although the plastic roof reduced incoming radiation (400–700 nm) by 20%, temperature and humidity was relatively unaffected. The plastic roof was sloped from 1.6 to 1.4 m above the soil surface. Sprinkling water runoff from the roof was collected in containers and then distributed to the respective plots via drip irrigation on the soil surface. Soil salinity measurements, taken at 0 to 30 cm in each of the plots with a four-electrode probe, indicated that soil salinity was similar under covered and uncovered sections of the plots. In 1990, average Cl_e concentrations from 0–30 cm for treatments one through five were 86, 98, 119, 140, and 166 mmol/l, respectively. These values were calculated from average soil EC_e values (dS/m) using the expression; Cl (mmol/l) $= -2.0 + 10.5$ EC (dS/m). Sprinkling with saline water began on 6 Feb., 23 Feb., and 31 Jan. in 1989, 1990, and 1991 and terminated on 2 June, 4 June, and 7 June, respectively. In 1989, leaves were sampled from plants on 6 April, 9 May and 23 May. In 1990, leaves were sampled on 16 April, 7 May, and 29 May. When the sampling date was before heading, the youngest most fully expanded leaf was sampled. When the sampling date was after heading, the leaf below the flag leaf (flag leaf-1) was sampled. At each sampling, leaves were green and healthy except for those taken on 29 May, 1990. On this date, many of the leaves sampled from uncovered plots at moderate to high levels of salinity were senescent or severely injured. In 1991, samples were taken on 21 May while most plants were still healthy. In this year, five samples, each containing two to three plants per sample, were taken in each of the five plots. The shoots in each sample were partitioned into seven separate components: (1) sheaths and culms; (2) heads; (3) peduncles; (4) flag leaf blades; (5) flag-leaf blades-1 (i.e., the leaf blades below the flag leaf); (6) flag leaf blades-2 (i.e., the leaf below flag leaf-1); and (7) old-leaf blades (i.e., all remaining leaves). No distinction was made between tillers and main stems before combining similar organs. At low salinity, only a small fraction of the "old leaves" were senescent at the time of sampling. At the other extreme, nearly all the "old leaves" from uncovered plants at high salinity were senescent as well as many of the "flag leaf-2" leaves. All other sampled leaves and tissues were green and healthy. The sampled plant material was washed two to three times with deionized water for 10 to 20 s to remove salts on the tissue surface, and dried in an oven at 70 °C to a constant dryness. The dry tissue was weighed and then ground in a blender. The chloride concentration in the plant tissue was determined on dilute nitric-acetic acid extracts of the ground plant material by the Cotlove (1963) coulometric-amperometric titration procedure.

Results

Shoot biomass

In 1991, increased salinity of the irrigation water significantly reduced the biomass of all seven shoot components, but not in the same proportion. The fraction of whole-shoot biomass comprised by a particular component depended upon the salinity level. Depending upon the particular shoot component, this fraction either increased, decreased or was not affected by increasing salinity (Table 2). The values in the table are slopes, intercepts, and correlation coefficients (r) from linear regression analysis of the fraction of shoot biomass relative to the irrigation water Cl concentration. The table shows that as salinity increased, the biomass of the head and peduncle became a larger fraction of the total shoot mass (i.e., positive correlation) while the biomass fraction of sheath plus culms and flag leaf became less (i.e., negative correlation). The mass fraction of the shoot components were affected by salinity the same, for the most part, regardless of whether they were covered or uncovered during sprinkler irrigation.

Table 2. Slopes, y-intercepts and correlation coefficients (r) from linear regression analyses of the dry weights of the given organs expressed as fractions of shoot dry weight, on the Cl concentration (mmol/l) of the irrigation water for the covered and uncovered treatments. Data from the 1991 experiment

Shoot organ	Slope		y-intercept		r	
	Covered	Uncovered	Covered	Uncovered	Covered	Uncovered
Flag leaf	-6.74×10^{-5}	-4.48×10^{-5}	0.021	0.018	−0.80	−0.53
Flag leaf-1	-7.30×10^{-5}	-1.69×10^{-5}	0.043	0.039	−0.67	−0.23
Flag leaf-2	-5.96×10^{-5}	-5.45×10^{-5}	0.046	0.045	−0.75	−0.47
Old leaves	1.60×10^{-5}	8.50×10^{-5}	0.095	0.099	0.09	0.43
Head	4.74×10^{-4}	6.34×10^{-4}	0.157	0.128	0.82	0.86
Peduncle	1.89×10^{-4}	2.19×10^{-4}	0.104	0.095	0.67	0.72
Sheath and culm	-4.65×10^{-4}	-8.34×10^{-4}	0.535	0.576	−0.73	−0.91

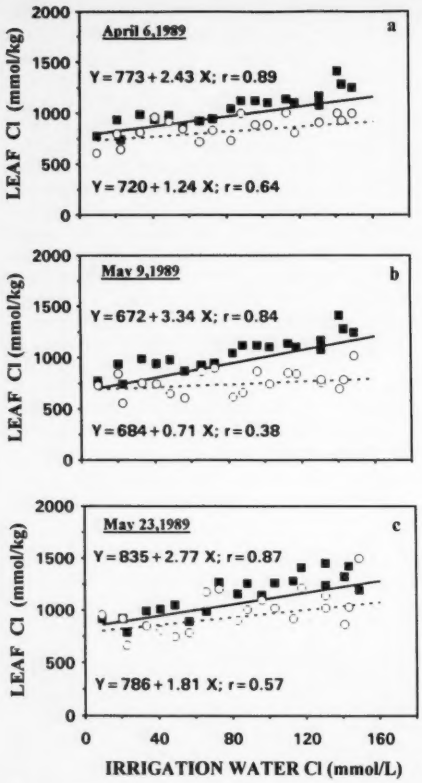

Fig. 1a–c. Leaf Cl concentration of covered (○) and uncovered (■) barley (cvs 'Albacete', 'Barbarrosa', 'Criter' and 'Igri') sampled at various times in 1989 in relation to the chloride concentration of the irrigation water

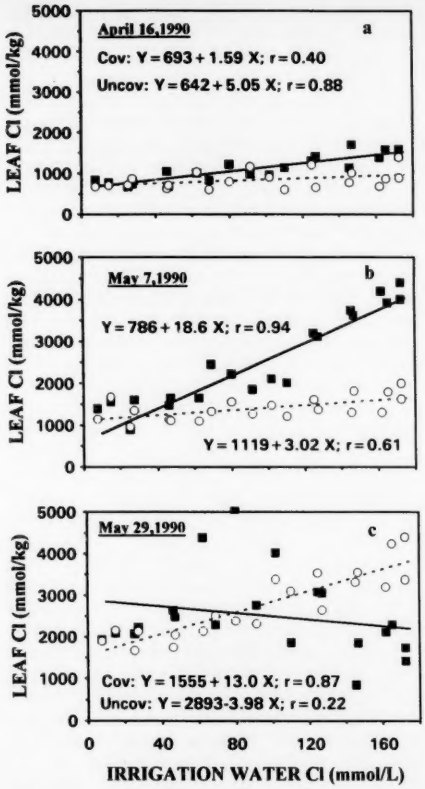

Fig. 2a–c. Leaf Cl concentration of covered (○) and uncovered (■) barley (cvs 'Georgie', 'Hassan', 'Patty' and 'Trait D'Union') sampled at various times in 1990 in relation to the chloride concentration of the irrigation water

Tissue Cl concentration

Leaf Cl concentration data indicate that both root and foliar absorption processes are responsible for leaf Cl accumulation. The extent to which each of these processes contribute to the overall concentration of Cl in the leaf varies among organs and with sampling time.

Linear regression analysis was conducted on the relationship between leaf Cl concentration and the Cl concentration in the applied water for each cultivar in both 1989 and 1990. No significant differences (i.e., $P > 0.05$) in slopes or y-intercepts were found among the different cultivars in either year. Consequently, data from the four cultivars in each of these years were combined.

In 1989, the Cl concentration in leaves from uncovered plants was linearly ($r^2 = 0.71$ to 0.79, $P < 0.001$) related to the concentration of Cl in the sprinkling water regardless of the sampling date (Fig. 1a–c). Leaf Cl concentration in covered barley plants (i.e., leaves that were not wetted during sprinkler irrigation) was not correlated as well with the Cl concentration of the irrigation water as those from uncovered plants and r^2 values ranged from 0.14 to 0.41 depending upon the date sampled.

As expected, differences in leaf Cl concentration between covered and uncovered barley plants were undetectable at low Cl concentrations in the irrigation water, but increased as the Cl in the water increased. Differences between the slopes of the relationship between leaf Cl and Cl in the irrigation water, between covered and uncovered treatments, are significant ($P < 0.05$) while there are no significant differences between the y-intercept values. This indicates that the relative contribution of Cl in the leaf from foliar absorbed salts increased with increasing Cl in the irrigation water.

In 1990, leaves from both covered and uncovered plants were sampled at three different times throughout the season similarly to the previous season. The four cultivars tested in 1990 were 'Georgie', Hassan 'Patty', and 'Trait D'Union'. Leaf Cl concentration data were again averaged and plotted (Fig. 2).

The data from the first two sampling periods (16 April and 7 May) were comparable to those from the previous year in that: (1) leaf Cl concentration from uncovered plants increased linearly ($r^2 = 0.77$ and 0.88) with increasing Cl concentration in the sprinkling water; and (2) there were no differences in leaf Cl between covered and uncov-

ered plants at low salinity but differences increased with increased Cl in the sprinkling water (i.e., slopes were significantly different). One difference between the data from this year and those of the previous year was that at high salinity (i.e., >120 mmol Cl/l) at the second sampling, most of the Cl in the leaves originated from foliar absorption. That is, the concentrations of Cl in leaves of uncovered plants (root plus foliar-absorbed Cl) were more than twice those from covered treatments (only root-absorbed Cl). The difference may be attributed to the cultivars grown. In 1989, winter cultivars were tested, whereas in 1990 spring cultivars were grown. Since spring cultivars mature earlier, leaves sampled at the same date would have been physiologically older than those of the winter cultivars.

Data from the third and latest sampling (29 May) in 1990 was unlike those from the previous year. In 1990, leaf Cl concentrations in covered plants at high salinity (>140 mmol Cl/l), were significantly higher than those from uncovered plants. Furthermore, the Cl concentration in sampled leaves from uncovered plants at high salinity was substantially lower than the previous sampling. For each cultivar, the concentration of Cl in sampled uncovered leaves increased with increased Cl in the sprinkling water to a maximum, which varied among cultivars, then decreased with increased Cl in the sprinkling water. Leaf Cl in covered plants, on the other hand, steadily increased as Cl in the sprinkling water increased.

Distribution of Cl among the organs of the shoot

In order to better understand the differences in results of the third sampling between the 1989 and 1990 years, covered and uncovered barley shoots were partitioned into various organs at the end of the 1991 season and analyzed for Cl. Tissue Cl concentrations in these organs are graphically expressed in Fig. 3.

In 1991, leaf Cl concentration in uncovered flag and flag-1 leaves was linearly related (r^2 0.78 and 0.86 respectively) to the concentration of chloride in the sprinkling water. Differences in leaf Cl between covered and uncovered plants progressively increased with concentration of Cl of the sprinkling water. This behavior was similar to those shown for the first two samplings in 1989 and 1990. This similarity is not surprising since all these leaves were relatively young. Thus, it is inferred that most of the Cl that accumulated in the flag leaves of uncovered plants from locations where Cl in the irrigation water exceeded 100 mmol/l was by foliar absorption. This assumes, however, that root and foliar absorption processes operate independently.

The 1991 tissue Cl data shown in Fig. 3 indicate that Cl was partitioned differently in covered than in uncovered barley shoots. Young tissues (e.g., the peduncles and head) contained the lowest concentration of Cl regardless of whether they were exposed to saline spray. This result was expected since these new organs had relatively little time to accumulate Cl as compared to older tissue. However, at the highest salinity level, heads and peduncles from uncovered plants contained significantly more Cl than those that were covered during sprinkling irrigation. The sheaths and culms, which contributed to approximately half the shoot biomass, contained a substantial amount of Cl and were responsible to a large extent for sequestering root-absorbed Cl from actively photosynthesizing leaf blades (Wolf et al. 1991).

Leaf Cl concentrations are of particular interest. At low salinity levels, leaf Cl of covered and uncovered plants was not significantly different but leaf Cl concentrations steadily increased from young to older leaves where concentrations reached a maximum within the flag leaf-2. At high salinity, the difference in leaf Cl concentration between covered and uncovered plants was maximum in the youngest leaf (flag leaf), but the difference became progressively smaller with increasing leaf age and concentrations in old leaves were highest in covered plants. In covered plants, leaf Cl increased with increasing Cl in the irrigation water, especially with increased leaf age. The slope of this relationship progressively increased (i.e., 0.87, 2.99, 4.03 and 5.71) as leaf age increased (i.e., flag, flag-1, flag-2, and old leaves). In contrast, leaf Cl in uncovered plants sampled at the end of the season, did not increase with increasing leaf age at the higher salinity levels. Instead, the slope of the relationship between leaf Cl and irrigation water Cl concentrations progressively decreased (i.e., 8.39, 6.71, 4.19, and 3.02) with increasing leaf age.

The effects of the interaction between salinity level and leaf age on leaf Cl concentration (mmol/kg) can be seen in Fig. 4. In this figure, the ratio of leaf Cl concentration in uncovered to that in covered plants at low, medium and high irrigation water Cl concentration is plotted in relation to the leaf position (leaf age) on the shoot. In all cases, the ratio decreases as leaf age increased. However, the decrease in the ratio was greater the higher the salinity level. As salinity increased, the ratio increased in younger leaves. In the flag leaf, the ratio was greater than two at high salinity indicating that most of the Cl in the leaf was from foliar absorbed Cl. However, in older leaves (i.e., flag leaf-2 and older), moderate to high salinity (72 to 188 mmol Cl/l) decreased the ratio of chloride concentration of uncovered leaves to that in covered leaves. In the oldest leaves, the ratio was less than unity at all salinity levels, emphasizing that the concentration of Cl in covered leaves was greater than that of leaves uncovered during sprinkler irrigation.

Discussion

Yield data, reported by Aragüés et al. (1994), indicate that saline sprinkling water reduced shoot biomass of barley more when plants were subjected to foliar wetting than when they were covered during irrigation. Furthermore, they demonstrated that leaf Cl concentration was linearly related (i.e., negative slope) to yield.

In these experiments, barley plants that were uncovered during irrigation exhibited substantially more foliar injury (i.e., chlorosis and necrosis), particularly in older leaves, than those covered during irrigation. This is not surprising since older leaves have a longer opportunity

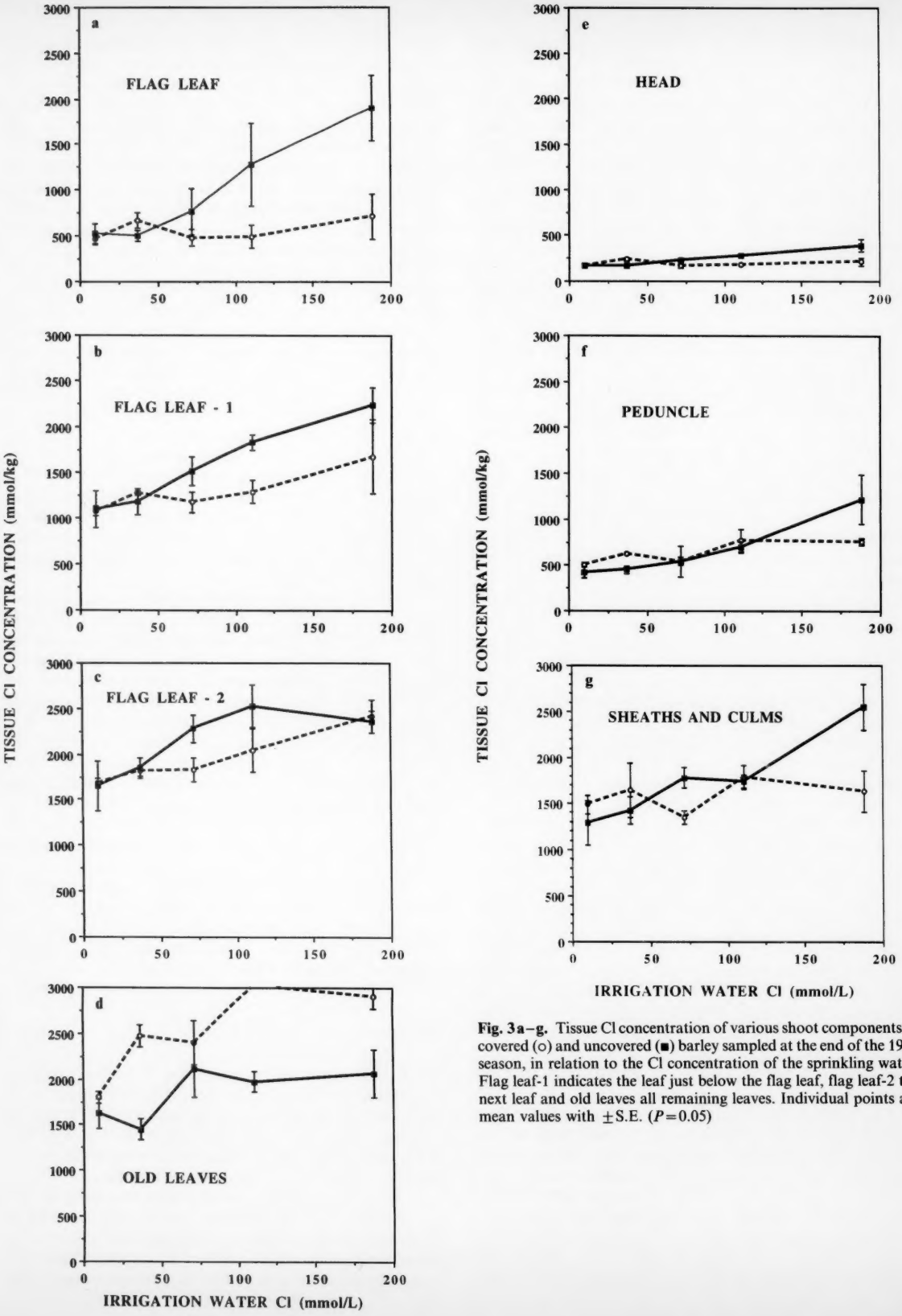

Fig. 3a–g. Tissue Cl concentration of various shoot components of covered (○) and uncovered (■) barley sampled at the end of the 1991 season, in relation to the Cl concentration of the sprinkling water. Flag leaf-1 indicates the leaf just below the flag leaf, flag leaf-2 the next leaf and old leaves all remaining leaves. Individual points are mean values with ±S.E. ($P=0.05$)

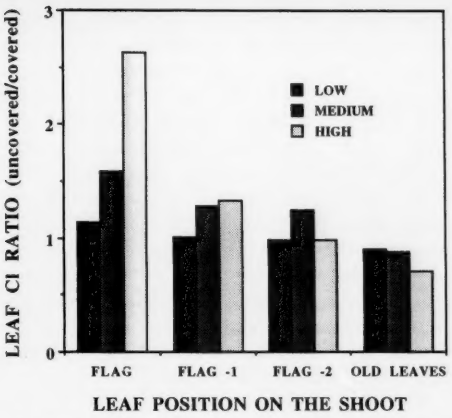

Fig. 4. Leaf Cl concentration ratio of those plants uncovered (foliar plus root-absorbed Cl) to those covered (root-absorbed Cl only) during sprinkler irrigation. Leaf Cl ratio's are for different aged leaves on the plant each at low, medium, and high levels of salinity. Data from the 21 May, 1991 sampling

to accumulate salt by foliar and/or root-absorption processes (depending upon the treatment) than do younger leaves.

Salinity affected the partitioning of dry matter in the shoot whether plants were covered during the irrigation process or not. In 1991, the organs associated with reproduction (e.g., heads and peduncles) comprised a larger fraction of the total shoot biomass under high salinity conditions than under low salinity. The biomass of other tissue, such as young leaves and sheaths plus culms, was a correspondingly smaller fraction of the total shoot weight under high salinity than under low salinity. This suggests that under salinity stress the plants were able to redistribute their dry matter to favor reproductive growth.

Leaf Cl concentration of young leaves sampled from plants that were uncovered during irrigations was in nearly all cases, linearly related to the concentration of Cl in the irrigation water. Equivalent leaves from covered plants also contained a substantial amount of Cl but leaf Cl concentrations were not as well correlated with Cl concentration in the irrigation water as salinity increased.

The extent by which foliar absorption or root absorption processes were contributing to overall leaf Cl concentration was dependent upon the shoot tissue and sampling date. The contribution of each process can be evaluated by two approaches. To assess the fraction of the leaf Cl that was derived from the soil via root absorption in comparison to that derived from the leaves via foliar absorption, it is appropriate to compare leaf Cl concentrations between covered and uncovered leaves at a given salinity level. If leaf Cl from plants that were uncovered (i.e., root plus foliar absorption) is more than twice that from the covered (i.e., root absorption only) treatment, then more than half of the Cl may be assumed to be derived from foliar absorption. On the other hand, a comparison of the slopes of the relationship between irrigation water and tissue Cl concentration in covered and uncovered treatments may indicate the relative importance of foliar and root absorption processes. Thus, if the slope of the uncovered treatment is more than twice that from the covered treatment, then the foliar absorption process dominates over the root absorption process in terms of foliar Cl accumulation. These comparisons are valid when y-intercepts are similar and assume that foliar absorption and root absorption processes are, for the most part, independent of one another in terms of leaf Cl accumulation. However, over the duration of the experiment, it is obvious that foliar absorption and root absorption will not always be entirely independent of one another. For example, due to differences in foliar injury, transpiration rates in uncovered plants towards the end of the season will likely be less than those that were covered during irrigations. Similarly, the cumulative transpiration of plants that were covered throughout the 1990 season may have been less than those that were uncovered. Since transpiration affects the transport of root-absorbed Cl within the plant, large differences in cumulative transpiration could affect root Cl accumulation.

We found that in the uncovered treatment, these slopes were more than twice those from the covered treatment indicating that foliar absorption was the dominant process in certain young leaves (i.e., those sampled 9 May 1989; 16 April and 7 May 1990; and 21 May 1991). Our explanation of this is as follows: Root-absorbed Cl accumulates in stems and older leaves of barley shoots while the young organs are protected against uptake and accumulation (Wolf et al. 1991). Therefore the concentration of Cl in young tissue from root absorption and translocation processes, is low relative to older tissue. This ion discrimination does not occur under foliar absorption processes and young tissue exposed to saline spray can readily absorb Cl in its tissue. It is hypothesized that salts enter the foliage through the cuticle rather than the stomata (Franke 1967; Haynes and Goh 1977). Differences in cuticular composition or thickness may exist between young and old leaves, thus resulting in a greater or lesser degree of salt absorption through the foliage. The tissue Cl concentration in peduncles and heads (both relatively young tissue) also increased linearly ($r^2 = 0.78$ and 0.84, respectively) with increased Cl in the irrigation water. The slopes of uncovered treatments were both more than twice their respective covered treatments indicating that direct foliar absorption by these organs was the dominant process responsible for Cl accumulation.

Some grasses appear to preferentially partition Cl to their sheaths relative to their blades (Greenway 1962) though this effect was found to be more pronounced in sorghum than barley (Boursier et al. 1987). In our study, sheaths were not separated from culms, yet their combined concentration of Cl along with their relatively high percentage of biomass, suggest that much of the total shoot Cl is present in these tissues.

There were two samplings where Cl in the leaves from uncovered treatments was more than twice that of the respective covered treatments. At the 7 May, 1990 sampling, chloride in the leaves from uncovered plots was more than twice that of covered plots at irrigation water

Cl levels in excess of 117 mmol/l. Similarly, flag leaves from uncovered plots sampled on 21 May, 1991 contained over twice the leaf Cl of those from covered treatments at irrigation water Cl levels in excess of 105 mmol/l (Fig. 4). In both these instances where leaf Cl in uncovered leaves was more than twice those in covered leaves, it is reasonable to conclude that a larger fraction of the Cl in the uncovered leaves originated from foliar absorption and that this process is mostly responsible for Cl accumulation. However, in all other instances where leaf Cl in uncovered leaves is less than twice that in covered leaves, one can not safely conclude that most of the Cl originated from root absorption processes. Since Cl influx into root tissue was found to be dependent, to some extent, upon internal Cl concentrations (Cram 1983), it may be possible that foliarly-absorbed Cl affects the accumulation of root-absorbed Cl in the leaf. Furthermore, leaf Cl accumulation in barley was found to be linearly related to the number of hours sprinkled in greenhouse studies for up to five weeks (Maas et al. 1982b). Additional sprinkling did not increase leaf Cl further. It is possible, therefore, that much of the Cl in older leaves of uncovered plants at higher salinity was derived from foliar-absorption sources during the first month of sprinkling, reaching maximal levels, and thereby restricting root-absorbed Cl that would otherwise be accumulating in the leaf if the plant was not wetted by saline water. Therefore, the assumption that foliar and root Cl absorption processes are independent of one another may be valid during early stages but not necessarily later on. This hypothesis warrants further testing.

Exposure of barley plants to saline spray caused leaves to prematurely senesce. Older leaves from uncovered plants at moderate to high salinity levels were severely injured. They were often much drier at the final sampling than those from covered plants and contained less Cl (Fig. 3, old leaves). This response was also observed on younger tissue at the final sampling in 1990 (Fig. 2, 29 May) and in an experiment conducted at this station in 1987 (data not shown) when uncovered leaves were substantially drier than covered leaves. Maas et al., (1982a) also noted that for the initial five weeks, foliar Na and Cl concentrations increased in the leaves of pepper plants that were sprinkle irrigated with saline water, but salt concentrations often decreased thereafter when leaves became injured and senescent. Although they suggested that Cl was more likely to be the cause of injury than Na, there was no consistent correlation between foliar injury and leaf Cl concentration. Although unlikely, during the desiccation process some of the Cl in the injured and often dry leaves from these studies may be translocated out of the leaves to other tissue. More likely, the leaf Cl concentrations are lower in older, often dry leaves than those from covered plants due to leaching of leaf Cl during late season sprinklings. In a very limited test in the laboratory, leaching of Cl from injured leaves during two, 30-s rinse periods with deionized water to remove leaf-surface salts, on the other hand, was found to be small (Grattan et al. 1981). Further examination of the leaching of ions from dry and senescent leaves is warranted.

These experiments demonstrated that barley shoots wetted by saline sprinkling water, readily accumulated Cl in their young leaves by direct foliar absorption. Furthermore, foliar absorption was more important for leaf Cl accumulation than was root absorption. However, leaf Cl concentration data from older leaves of plants that were covered and uncovered can not be used to determine the fraction of leaf-Cl that accumulated from root absorption versus that from foliar absorption. Controlled solution culture studies with labeled Cl in the growth media and non-labeled Cl in the sprinkling water is needed to advance our understanding of the interactions between these two absorption processes and determine the source of the leaf Cl (i.e., foliar versus root absorption) among different aged leaves.

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An analysis of the effects of water stress on leaf growth and yield of three barley cultivars

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Abstract. The main objective of the study was to evaluate the sensitivity of Iraqi local barley cultivar (Black) to soil water deficit as compared to other barley cultivars, namely: CM-72 and Arivat. The local cultivar proved to be susceptible during germination and emergence, but it developed resistance during the vegetative growth and yield formation stages. Growth analysis of individual leaves clearly showed that Black barley produced leaves of long growth duration which could affect the growth processes especially cell division. Thus, the reduction in the number of cells composing those leaves was small in the cultivar Black. Leaf growth rates as soil matric potential decreased, were reduced considerably, although, no clear trends were observed between cultivars. On the other hand, the smaller cell volume of local cultivar may have a role in its ability to tolerate water deficit. Some evidence that the local cultivar is post-flowering resistant is discussed.

The need to develop crops with higher tolerance to environmental stresses has increased tremendously in the last twenty years. A genetic approach has been adopted to develop some crop species that can tolerate environmental stresses (Epstein 1983; Krizek 1984). There is considerable evidence that genetic variability in sensitivity to water stress exists within crop species such as barley, wheat, sorghum, and pearl millet (Omara 1987; Bidinger et al. 1987; Winter et al. 1988). This can be considered as experimental materials for comparative studies in stress physiology, and may lead to discovery of structural, physiological and biochemical features consistently associated with the ability to tolerate drought (Morgan et al. 1986; Wenzel 1987; Morgan 1988; Rascio et al. 1990). Moreover, such studies may provide plant breeders with information to screen genotypes that can withstand water stress. However, hypothesis concerning specific plant characteristics which may be associated with drought resistance can be developed mainly through knowledge of: (1) growth variables (rate and duration) and the contribution of growth processes (cell division and expansion) to plant growth (Yasseen 1983; Yasseen et al. 1987), and (2) performance of crop plants under stress conditions (Winter et al. 1988; Al-Maamari 1989). This study was conducted to investigate the importance of growth variables and the contribution of growth processes to plant growth and yield, and the possibility of using these parameters in screening methods for drought resistance in barley. Also, the study included a comparative evaluation of resistance to water stress of Black barley which is considered to be tolerant to water stress and salinity (Yasseen et al. 1987; Al-Maamari 1989).

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Materials and methods

Plant material and soil

Three barley cultivars were chosen for the study, California Mariout-72 (CM-72), and Arivat, (Hordeum vulgare L.), and an Iraqi local cultivar, Black, (Hordeum distichum L.). Some agronomic, genetic and physiological characteristics of these cultivars are given in Table 1. Seeds of CM-72 were obtained from R. C. Sherwood Grain Co. Los Banos, California 93635 U. S. A. in November 1989, while seeds of Arivat and Black were obtained from Testing and Certification Branch, The Ministry of Irrigation and Agriculture, Mosul, Iraq, in October 1989. The viability test for all these seeds showed that 97 to 99% of the seeds used were viable.

The soil, a silty clay loam, used in the study was obtained from Rabeaa area (about 120 km north of Mosul) from the Northern Irrigation Jazera Project. The soil chemical and physical properties are listed in Table 2.

Treatments and rewatering method

Four moisture levels were determined from a standard curve relating soil matric potential to soil moisture content. The relationship was derived according to the method described by Richards (1954), using the pressure cooker technique to determine high matric potentials and the pressure membrane technique to determine low matric

Table 1. Some agronomic, genetic and physiological characteristics of three barley cultivars

Cultivar	Origin	Length of growing season (days)	Tiller number per plant	Yield (kg ha^{-1})	Spike type	Number of grains per spike	Protein content in the grain (%)	Salt tolerance
CM-72	U.S.A.	Short*	Few	High*	Six-row	*	*	Tolerant
Arivat	U.S.A.	Short (155–160)	Few	High (3000)	Six-row	60	9	Sensitive
Black	Iraq	Long (180–210)	Many	Low (1200)	Two-row	26	19	Tolerant

* No documented data in Iraq

Table 2. Chemical and physical properties of the soil

Properties	Values
pH (water extract)	7.8
Sat. Ext. ECe (mS cm^{-1})	0.62
Sand (g kg^{-1} dry soil)	27
Silt (g kg^{-1} dry soil)	677
Clay (g kg^{-1} dry soil)	296
Exch. Na (meq kg^{-1} dry soil)	0.89
Exch. K (meq kg^{-1} dry soil)	8.60
Ca (meq dm^{-1})	4.4
Mg (meq dm^{-1})	3.0
S (meq dm^{-1})	3.3

Table 3. Effect of soil matric potential on seedling emergence, as a percentage of control, of three barley cultivars after 14 days from sowing

Soil matric potential (MPa)	Black	Arivat	CM-72
Field capacity (−0.03)	100	100	100
−0.2	115	96	92
−0.6	68	101	104
−1.0	9	100	67

Cultivars: $P < 0.001$
Treatments: $P < 0.001$
Interaction: $P < 0.001$

potentials. Each level was prepared by adding appropriate amount of water to the soil, mixed thoroughly, to ascertain complete homogenization as well as avoiding aggregation of soil particles. These levels were −0.03 (field capacity), −0.2, −0.6 and −1.0 MPa. Seeds were sown in plastic pots, 15 × 15 × 20 cm in size, each holding 4 kg dry soil. All treatments were replicated three times, and distributed randomly inside a glasshouse. Seedlings were thinned to four per pot after emergence had stopped in each treatment; 14 days after sowing in −0.03, −0.2, and −0.6 MPa; and 21 days at −1.0 MPa. The experiments were conducted during the period January to April 1990 under natural conditions of light with photosynthetically active radiation (PAR) of 26 to 35 W m^{-2} and with average relative humidity ranging from 52 to 68%. The glasshouse was heated during the winter by electric heaters to maintain the temperature in the range of 18 to 23 °C.

Maintaining the water content of soil, and consequently the specified matric potential during germination, was accomplished by covering the pots with pieces of nylon to prevent evaporation of water from the soil surface until seedling emergence had stopped. During this period there was no need to rewater plants since changes in the weight of pots were not observed. However, during subsequent stages of growth and development the water content of the soil was maintained to the specified levels by adding distilled water every two days to the pots in holes of 10 cm in depth and 2 cm in diameter, in the center of the pots to hold them at their original weights, and to ensure water diffusion equally throughout the soil. Moreover, additional amount of water was added to the soil, in the same way, representing what the fresh weight of the growing plants can add to the original weight of pots. Estimation of fresh weights of growing plants was done weekly on extra plants grown under the same treatments.

Measurements

Seedling emergence. Twenty five seeds were sown in each pot, and the emergence of seedlings was followed daily and determined after fourteen days under the different levels of soil matric potential.

Leaf growth. Leaf length was determined daily, by a ruler, from the beginning of emergence of the leaf tip from the sheath until appearance and exposure of its ligule. This was done for the third and fifth leaves. The growth of these leaves was analyzed according to the equation and method described by Gallagher (1979). The equation used was: $F = (R \times D) + 0.1\ F$, where F is final length (cm), R is growth rate (cm day^{-1}) and D is duration of growth (days). This equation has been used to describe leaf growth in several barley cultivars (Yasseen et al. 1987).

The area of individual leaves (third, fifth and flag), and the remaining leaves on the main stem were determined according to the method described by Watson (1937), Aase (1978) and Yasseen et al. (1988).

Cell number and volume. The number and volume of cells were determined using the technique described by Sunderland (1960), and, modified by Yasseen (1983). Cells were counted using a double chambered Hawksley haemocytometer slide. The cell volume was estimated by the following formula, assuming that the cell density is equal to the density of water:

$$\text{Cell volume} = \frac{\text{Fresh mass/Cell density}}{\text{Cell number}}.$$

Yield. Plants were harvested at the end of the season. Total number and weight of seeds, and the weight of 1000 seeds were determined.

Results

Growth and yield

Seedling emergence, leaf area and yield were reduced as the soil matric potential decreased, but the cultivars differed significantly in their response to water shortage at different stages of growth. For example, Arivat and CM-72 were more tolerant than the local cultivar during germination and seedling stages (Table 3). The reduction in the percentage of seedling emergence of Black was substantial especially at the lower levels of soil matric potential. During subsequent growth stages, however, the local cultivar seemed to gradually develop resistance

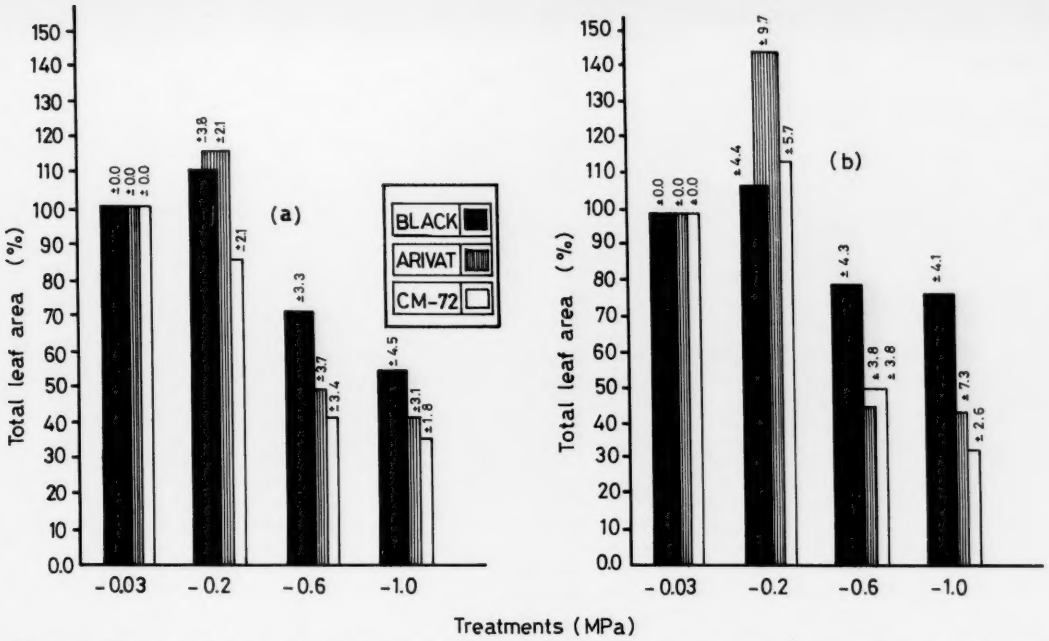

Fig. 1a, b. Effect of soil matric potential on the leaf area of the main stem, as a percentage of control, 50 **a** and 100 **b** days after sowing in three barley cultivars. The figures on the top of bars represent the standard errors of the means

Table 4. Effect of soil matric potential on the number and weight of seeds of three barley cultivars

Soil matric potential (MPa)	Number of seeds/plant			Weight of seeds (g plant^{-1})			1000-seeds weight (g)		
	Black	Arivat	CM-72	Black	Arivat	CM-72	Black	Arivat	CM-72
Field capacity (−0.03)	45.3	33.6	30.3	1.70	1.47	1.52	37.5	43.6	50.3
−0.02	38.3	22.6	19.3	1.47	1.03	0.85	38.4	45.6	45.3
−0.6	18.0	9.6	10.3	0.66	0.30	0.33	37.3	31.4	33.7
−1.0	14.0	10.6	6.0	0.49	0.32	0.19	36.0	31.0	32.9
Cultivars	: $P < 0.001$			: $P < 0.001$			: N.S.		
Treatments	: $P < 0.001$			: $P < 0.001$			: $P < 0.001$		
Interaction	: N.S.			: N.S.			: $P < 0.01$		

to water stress. The reduction with water stress in the total leaf area on the main stem was considerable in Arivat and CM-72 compared to the local cultivar (Fig. 1). This large difference between the three cultivars became more pronounced at the end of the season. The data of yield components showed almost the same trend found in the vegetative growth (Table 4). The cultivar Black had more seeds and these seeds were heavier than the other two cultivars at lower soil matric potentials. Also, it is interesting to note that the 1000-seeds weight showed that the cultivar CM-72 produced the biggest seeds with no stress followed by Arivat, while the cultivar Black had the lowest seed weight. However, under stress conditions, the reduction in the 1000-seeds weight was substantial in CM-72 followed by Arivat, while the reduction in Black cultivar was the least.

Growth processes

The reduction in leaf area due to water stress can be attributed mainly to the reduction in cell number and cell volume. The reduction in both growth processes was highly significant especially at the lower soil matric potentials. There were obvious differences among the three cultivars in the area of individual leaves as well as the number of cells in those leaves (Tables 5 and 6). At low soil matric potentials the reduction in the number of cells was substantial in the cultivars CM-72 and Arivat compared to Black, whereas no clear differences were found between these cultivars in the volume of cells (Table 7), with one exceptional case that the cell volume in flag leaf of CM-72 at −1.0 MPa was reduced considerably (about 42%).

Table 5. Effect of soil matric potential on the final area (cm^2) of leaf 3 and 5 and flag leaf of three barley cultivars

Soil matric potential (MPa)	*Leaf 3* Black	Arivat	CM-72	*Leaf 5* Black	Arivat	CM-72	*Flag Leaf* Black	Arivat	CM-72
Field capacity (−0.03)	9.8	12.0	12.6	9.7	12.0	7.5	1.8	1.7	5.2
−0.2	10.7	10.7	10.2	10.4	13.2	5.7	1.3	1.2	3.7
−0.6	8.0	9.4	5.7	7.4	2.7	1.6	1.4	0.7	1.6
−1.0	7.6	6.2	3.0	7.2	2.4	0.9	1.3	0.6	1.7
Cultivars	: N.S.			: $P < 0.001$			: $P < 0.001$		
Treatments	: $P < 0.001$			: $P < 0.001$			: $P < 0.001$		
Interaction	: N.S.			: $P < 0.01$			: $P < 0.01$		

Table 6. Effect of soil matric potential on cell number (10^6) in leaf 3 and 5 and flag leaf of three barley cultivars

Soil matric potential (MPa)	*Leaf 3* Black	Arivat	CM-72	*Leaf 5* Black	Arivat	CM-72	*Flag Leaf* Black	Arivat	CM-72
Field capacity (−0.03)	3.914	3.643	2.752	3.355	3.456	2.352	0.632	0.700	1.450
−0.2	4.100	3.872	1.900	3.637	3.765	1.910	0.448	0.529	1.228
−0.6	2.907	3.291	1.594	2.359	0.827	0.399	0.406	0.262	0.592
−1.0	2.840	2.220	0.826	2.514	0.876	0.209	0.435	0.180	0.698
Cultivars	: $P < 0.001$			: $P < 0.001$			: $P < 0.001$		
Treatments	: $P < 0.01$			: $P < 0.001$			: $P < 0.001$		
Interaction	: N.S.			: N.S.			: N.S.		

Table 7. Effect of soil matric potential on cell volume (mm^3) in leaf 3 and 5 and flag leaf of three barley cultivars

Soil matric potential (MPa)	*Leaf 3* Black	Arivat	CM-72	*Leaf 5* Black	Arivat	CM-72	*Flag Leaf* Black	Arivat	CM-72
Field capacity (−0.03)	57	64	96	52	58	67	61	53	86
−0.2	48	48	92	49	62	52	52	43	52
−0.6	45	51	63	50	49	52	56	47	61
−1.0	39	42	57	47	44	58	52	59	36
Cultivars	: $P < 0.001$			: N.S.			: N.S.		
Treatments	: $P < 0.001$			: N.S.			: $P < 0.01$		
Interaction	: N.S.			: N.S.			: $P < 0.05$		

Table 8. Effect of soil matric potential on the growth rate (cm day^{-1}) of leaf 3 and 5 of three barley cultivars

Soil matric potential (MPa)	*Leaf 3* Black	Arivat	CM-72	*Leaf 5* Black	Arivat	CM-72
Field capacity (−0.03)	2.30	1.96	2.74	2.15	2.60	1.77
−0.2	1.85	1.73	2.13	1.94	2.50	2.00
−0.6	1.74	2.23	2.14	1.53	1.56	1.08
−1.0	1.79	1.88	1.56	1.39	1.63	1.17
Cultivars	: $P < 0.05$			: $P < 0.01$		
Treatments	: $P < 0.001$			: $P < 0.001$		
Interaction	: $P < 0.01$			: N.S.		

Table 9. Effect of soil matric potential on the duration of growth (days) of leaf 3 and 5 of three barley cultivars

Soil matric potential (MPa)	*Leaf 3* Black	Arivat	CM-72	*Leaf 5* Black	Arivat	CM-72
Field capacity (−0.03)	8.0	9.6	7.9	10.3	8.4	6.3
−0.2	10.4	9.9	9.1	11.0	9.1	5.7
−0.6	9.4	8.5	7.3	9.9	5.6	5.5
−1.0	9.0	8.5	7.9	11.5	4.7	4.3
Cultivars	: $P < 0.01$			: $P < 0.001$		
Treatments	: $P < 0.01$			: $P < 0.01$		
Interaction	: N.S.			: $P < 0.01$		

A reduction in growth processes can be explained by a reduction either in the rate and/or duration of those processes. In the present study the main reduction in the length and area of leaves due to soil water deficit was attributable to the reduction in both rate and duration in CM-72 and Arivat, (Tables 5, 8, and 9), whereas the growth duration of leaves in Black did not change with water deficit. A reduction in the growth rate of leaves was the main reason for the reduction in the length and area of the local cultivar with water deficits.

Discussion

The present findings indicate that cultivars differ in their reaction to soil water deficit during various stages of their life cycle. CM-72 is tolerant during germination and seedling emergence, while the local cultivar proved to be susceptible during those stages. The latter cultivar seemed to gradually build up a degree of tolerance to water deficit with age, so it had a larger area of leaves under all levels of soil matric potential compared to the other cultivars. Moreover, its superiority over the other cultivars may become more obvious during the post-anthesis period and at maturation (Davidson and Birch 1978; Al-Maamari 1989). The local cultivar was sensitive to salinity during germination and early seedling stage, but tolerant during the vegetative growth period (Yasseen et al. 1987 and 1988). Changes in the colloidal-chemical properties of the cytoplasm with respect to osmotic stress could be a reason for changes in sensitivity to water deficit during different stages of growth and development (Levitt 1980). CM-72 has been considered to be salt tolerant during germination and seedling stage (Ayers et al. 1952; Norlyn 1980), and may be tolerant to water deficit conditions. However, CM-72 proved to be less tolerant than the local cultivar during the vegetative growth period in the present experiments. Therefore, there is no particular stage in the crop life cycle that can be exploited for reliable screening tests, since the sensitivity to osmotic stress changed dramatically during the different stages of crop growth and development. Unfortunately much of successful work with breeding programmes and screening techniques done during the last decade were based on a particular stage of the crop life cycle (Epstein et al. 1980; Blum et al. 1980; Epstein 1983; Omara 1987). Moreover, large scale screening techniques for breeding drought resistance in winter wheat have been used (Winter et al. 1988) with limited success for the determination of physiological characteristics that can be considered as important criteria in selecting wheat cultivars suitable for cultivation in the semi-arid areas, and for breeding programmes in the development of cultivars resistant to drought. Therefore, much work remains to be done to develop and improve screening techniques for drought resistance, since, breeding for such conditions has been limited by a lack of simple screening methods, and a lack of evidence that the methods employed would result in improved yield stability under drought. One possible method which seems worthwhile is by increasing the length of the growing season, and if leaves are able to expand rapidly under drought and salinity stresses, may lead to considerable maintenance of yield under these conditions (Monteith 1977). It has been shown that long-season cultivars of wheat are generally more tolerant to salinity during the vegetative growth and yield formation periods than short-season cultivars (Torres-B and Bingham 1973; Torres-B et al. 1974). Leaf growth in several cultivars under salinity stress was described quantitatively using logistic equations and the derived variables were calculated from such description (Yasseen 1983). Faster rates and longer durations of growth of individual leaves were found in long-season cultivars than in short-season cultivars. This was considered an important criterion in selecting wheat cultivar suitable for cultivation in saline soils, and for breeding programmes to develop salt tolerant cultivars. Data of this study confirm the importance of growth variables (rate and duration) in the evaluation of barley cultivars in their tolerance to water deficit. It is likely that longer duration of growth processes in leaves of the local cultivar led to a larger leaf area, and to more and larger seeds under conditions of water deficit compared to the other cultivars. Moreover, these leaves had more cells, indicating that the process of cell division in the local cultivar is relatively less sensitive to water deficit (Uchimiya and Takahashi 1973; Yasseen et al. 1987; Al-Maamari 1989). However, cell volume in these cultivars was reduced in a similar manner with stress, but the small volume of cells in leaves the local cultivar may have a role in resisting water stress (Cutler et al. 1977).

Finally, it is interesting to note that Arivat was almost as sensitive as CM-72 to water deficit. This unusual observation needs further investigation considering its adaptation to the environmental conditions in Iraq.

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Book reviews

Alscher RG, Cumming JR (eds): Stress responses in plants: adaptation and acclimation mechanisms. Wiley-Liss, New York, 1990, xii, 407 pp, US $ 103.00

This book highlights the ephemeral nature of science and rapid progress that is being made in understanding adaptation and acclimation to environmental stresses. Ten years ago, this reviewer and P. J. Kramer edited a book, produced by the same publisher, entitled *Adaptation of Plants to Water and High Temperature Stress*. None of the authors in that book is an author in the present volume and only six of the papers published in the earlier book are cited in the book under review. In part this is because the scope of the present book is broader than its predecessor which was restricted to water and high temperature stresses. The authors in the present volume also address anthropogenic stresses such as ozone and heavy metals, and include cold temperature stress as well as water and high temperature stress.

The book has 17 chapters contributed by 30 authors, principally located in North America, but including a few from Germany, Sweden and the United Kingdom. The book commences with two chapters by Amthor and McCree and by Setter on the carbon balance and assimilate partitioning, respectively, of plants subjected to stress. While photosynthesis plays a key role in both of these processes, the role of stomata is not discussed until Chapter 11 in which Mansfield and Atkinson review the responses of stomata to water deficits with particular reference to the role of abscisic acid. The third chapter deals with the mechanisms that plants utilise to cope with desiccation, a state that the author, Leapold, points out is only transient. The fourth chapter by Winston discusses the formation of free radicales in cells in response to a range of stresses, but it is hard for this reviewer to see how this chapter and the ones by Hassan and Scandalios (Chapter 8) on superoxide dismutases and Smith and co-workers (Chapter 9) on glutathione as an antioxidant are relevant to adaptation and acclimation mechanisms in plants. Young and Britton in Chapter 5 review the role of carotenoids in light harvesting and in the protection of chloroplasts against photooxidation. However, carotenoids are also subject to photooxidation leading to photoinhibition and the destruction of chlorophyll and carotenoids when other stresses, such as water stress, occur at high light intensities. Since carotenoids are thought to be precursors of abscisic acid, the chapter by Morgan (Chapter 6) on the role of biotic stresses on plant hormones is a logical subsequent chapter. Morgan emphasises the role of abscisic acid and cytokinins, suggesting that abscisic acid increases as a result of almost all stresses, whereas cytokinins decrease in those stresses in which their responses have been studied. Morgan also briefly discusses auxins and giberellins, but leaves the role of ethylene to Wang and co-workers to review in the following chapter. Interestingly, these authors discuss the role of ethylene as an air pollutant as well as its production by the plant in response to chilling, waterlogging, water shortage and chemical stresses.

The book then moves on to review the role of superoxide dismutases and glutathione under stress conditions, as mentioned above, before Flores (Chapter 10) points out that polyamines, notably putrescine, increase significantly in response to a series of stresses. Although polyamines are thought to be involved in the regulation of cell division and cell differentiation, Flores concludes that "at this point we cannot conclude if this (increase in putrescine) is part of a protective response or part of the syndrome of toxicity observed under such conditions". Chapters 12 and 13 by Hällgren and Öquist and by Burke, respectively, deal with the adaptation and acclimation of plants to low and high temperature stress, respectively, with Burke introducing readers to the concept of thermal kinetic windows. This is the temperature range over which enzymatic activity is maximal; while this varies with species, plant enzymes do not appear to acclimate to changes in temperature. Burke reviews the influence of high temperatures on photosynthesis and carbohydrate metabolism, but does not discuss the role of heat shock proteins which are comprehensively reviewed by Vierling in Chapter 16. Chevone et al. in Chapter 14 point out that water deficits reduce the influence of damage by the air pollutant, ozone, and that increasing the adaptation of plants to water deficits can make the plants more susceptible to ozone. This is a good example of the interaction between stresses that must always be taken into account when studying environmental stresses. Chapters by Cumming and Taylor (Chapter 15) and Steffens (Chapter 17) on heavy metal tolerance and the role of photochelatins as metal-binding polypeptides produced in response to heavy metal stress conclude the book.

The book is well produced and only one typographical error was detected by this reviewer. It has a useful subject index, but no author index. As may be clear from the comments above, this reviewer had difficulty with the order in which the editors placed the chapters. Some overlap and redundancy between chapters has occurred, as may be expected in a multi-author volume, but this is not excessive. The book will be of greatest benefit to graduate students and researchers working in stress physiology. A recurring theme by almost all authors is the lack of knowledge in the field under review and the need for further research. For example, Vierling (Chapter 16) concludes that "the exact function of any heat shock protein is not yet known" and Steffens (Chapter 17) points out that "the mechanisms of plant adaptation to metal stresses are complex, and a great deal of biochemical, physiological, and molecular work needs to be done before we

reach a complete understanding of this system". Despite the efforts by the editors to develop a series of papers that enable general principles on the adaptation and acclimation to be developed, this reviewer was disappointed that no such general principles were identified. Morgan (Chapter 6) comes the closest to identifying a role for hormones in acclimation of plants to a range of stresses, but even he concludes that "it is probably safe to say that there are few cases where a regulatory role for a hormone in a particular stress has been unquestionably established".

Is this a book that will interest readers of Irrigation Science? There is little that deals directly with irrigation. Burke in Chapter 13 demonstrates that irrigation helps to maintain leaf temperatures within the thermal kinetic window during periods of high ambient temperature. Clearly, the chapters dealing with water deficits are of interest to those involved with irrigation practice in regions where water is in limited supply or expensive, and the role of waterlogging as a stress must be of concern to students and practitioners of irrigation. However, the chapters dealing with heavy metals, air pollutants (except where they interact with water shortage or excess), and photooxidants are likely to be of only marginal interest. It is a worthwhile record of the current (1990) state of knowledge in aspects of stress physiology and as such it is worthy of a place in your library, but I cannot recommend that irrigation scientists should have a personal copy on their desk.

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United Kingdom Register of Research and Irrigation, Drainage and Flood Control. International Commission on Irrigation and Drainage, British Section. Hydraulics Research, Wallingford, 1992, 93 pp

The initiative to compile the United Kingdom Register came from the British National Committee of the International Commission on Irrigation and Drainage (ICID), and the disciplines covered reflect, to a large extent, the interest of ICID members. The reception given to the first (1986), second (1988) and third (1990) issues of the Register has shown that it is an accepted reference work within the profession. In spite of the availability of technical journals and a number of national and international conferences, practicing planners, agriculturalists and engineers are not always aware of the research being undertaken and are therefore not able to fully utilise the results. The Register helps to meet the need for dissemination of such information.

The fourth (1992) edition sets out relevant UK research during the two years period January 1990 to June 1992. The 196 research entries (compared to 228 entries in the third edition) have been organized under three headings which are sub-divided into eleven subject areas:
1. *Irrigation* – hydrology, agriculture, engineering, management.
2. *Drainage and Flood Control* – agriculture, river engineering, policy and management.
3. *Related Topics* – monitoring and evaluation, sociology and economics, health, environment.

Each entry comprises project details, publications, sponsoring agency and names and addresses of researchers to contact for further information. Each entry is indexed under subject, researcher, location and institution. A section of institutional entries from 13 principal institutions conducting or sponsoring research in these areas is also included describing the organization and the type of work undertaken.

As with previous editions, the Overseas Development Administration, which funds a large number of projects, has helped to finance the publication and distribution of this edition. The Register is compiled and published by the Overseas Development Unit of Hydraulics Research, Wallingford, and copies are available from: Research Register Coordinator, Overseas Development Unit, HR Walingford, Howbery Park, Wallingford, Oxon OX10 8BA, UK.

Amir Kassam, 88 Gunnersbury Avenue, Ealing, London W5 4HA, UK

Shalhevet J., Liu Changming, Xu Yuexian (eds) Water use efficiency in agriculture. Priel Publishers, Rehovot, 1992, 297 pp.

This volume is the proceedings of a binational workshop held in Bijing, China during April 1991. The proeedings consist of papers by seven Israeli and nineteen Chinese scientists. The primary topics concentrated on the environmental aspects of irrigation including salinity and climate, crop response to water, and irrigation technology. The objectives of the workshop were to: (1) address the importance of water conservation in China, (2) identify methods that have been successful for improving water use efficiency in both China and Israel, and (3) review Israel's experiences in alleviating its own water deficiencies.

The seven Israeli papers summarized irrigated agriculture in Israel today. One paper described how Israel's agriculture has been transformed from "an extensive, largely self-dependent cropping system based on rainfall into an intensive, open system relying on fossil fuel-based inputs of water and agrochemicals to produce high-value horticultural crops for export". During this transition Israeli crop yields doubled per unit of applied water and water use per unit of irrigated land decreased 30%. As impressive as these achievements are, the author surmised that the current water use efficiency has to double by the end of the century for Israel to remain competitive on a global basis. This goal for water use efficiency is to be achieved while eliminating the negative consequences of intensive irrigated agriculture on the quality of water resources.

The other Israeli papers dealt with specific issues that must be addressed to achieve this goal. One paper de-

scribed strategies to manage saline soils and waters. The potential use of sewage effluent to supplement water resources was assessed with the major concerns described being bacterial contamination, heavy metals, salinity, sediment, organic substances, and nutrients. An excellent presentation on uniform irrigation applications suggested that uniformity be treated as a control variable rather than as a predetermined value. Although complete irrigation uniformity is unattainable and generally not economically desirable, low uniformity was shown to lead to significant yield loss and have serious environmental consequences. Models describing sea water intrusion, a major issue along any coast, were presented along with several practical applications. A relatively new technique to measure the flow of sap up the stems of plants has been developed to estimate transpiration. The ratio of transpiration, measured as sap flow, and potential transpiration was found to be 0.3 for citrus, 0.5 for pine, and 0.8 for both corn and cotton.

The majority of the Chinese papers addressed efficient water resource utilization on the North China Plain. This Plain constitutes one-third of China's flatland and accounts for over 1.8 million hectares of cultivated land. Since 1949, 7 100 reservoirs have been built to control the runoff of rivers transversing the North China Plains and 1.4 million tube wells have been installed to pump 60% of the groundwater recharge. The environmental issues raised because of excess use of water resources include soil salination, groundwater depletion, sea water intrusion, and sediment. Modelling efforts described for the North China Plains included the conjunctive use of surface and groundwater to increase water use efficiency and control salinity, the most effective cropping patterns and rotations to match water demand with water resources, and water management strategies to improve crop water use efficiency.

Wheat and cotton are the dominate crops on the Plains so that several papers dealt with improving water management of these crops. The potential for saving water at the initiation of peach fruit enlargement by withholding irrigation and then irrigating fully as fruit development proceeded was reported to increase production. Another specific topic under study in China was the use of mulches and plastic films to conserve water and maintain production. Similar to studies elsewhere, wheat production was found to increase linearly with applied water until 200 mm of irrigation had been applied in three irrigations. With respect to total crop water use (irrigation, rainfall, and stored soil water), wheat yields increased linearly up to 500 mm. One report indicated that drip irrigation systems designed specially for Chinese conditions were successful for grain, cotton, and oil crops.

One of the major contributions of the proceedings was the documentation of environmental concerns on the North China Plains. Reports indicated that about 2 million hectares of salt-affected soils now exist in the Plains; the rate of water table decline in areas like Cangzhou are as much as 5 m per year with more than 7 000 km^2 affected by declining groundwater; the density of tube wells near the sea coast is more than 19 wells per km^2 with the water table now being 5 to 10 m below sea level; and along the lower reaches of the Yellow River more than 200 million Mg of sediment are deposited annually. Due to one or more of these factors, the irrigated area has decreased recently by more than 140 000 ha, the average water table elevation during the last 20 years has declined 6 m, and the amount of stream flow reaching the sea is now only 6% of the flow 40 years ago.

The reports in this volume serve to highlight the urgent need for enhanced water use efficiency in both China and Israel. This issue is not unique to these two countries. In every country in the world practicing irrigation, these same issues are paramount. I strongly recommend the proceedings of this workshop to all concerned with food production, water resource protection, and enhancement of the environment.

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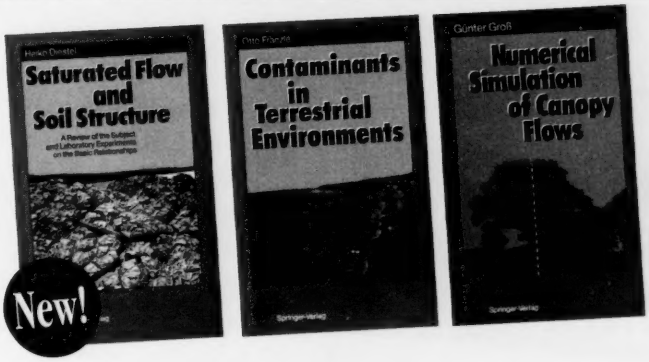

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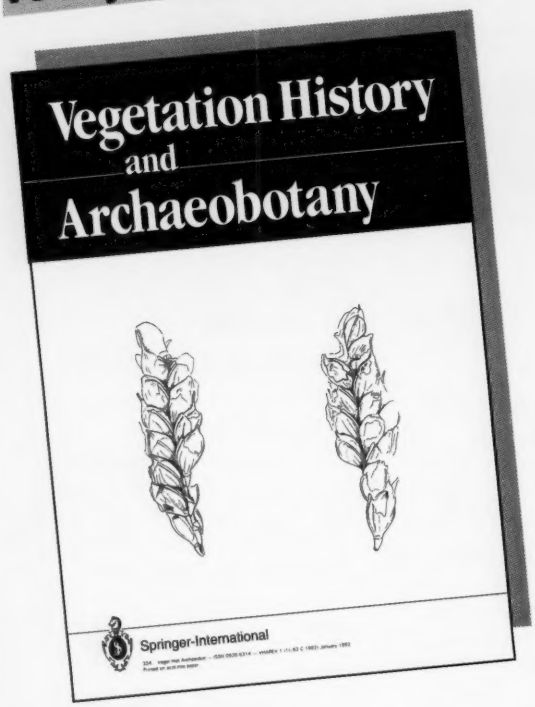

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